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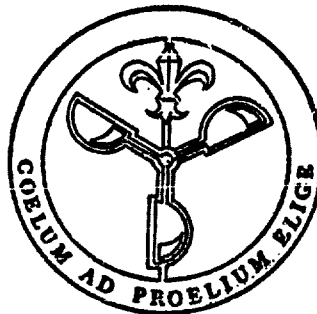
**AIR WEATHER SERVICE TECHNICAL REPORT**

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**TROPOPAUSE ANALYSIS  
AND  
FORECASTING**

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**MARCH 1952**

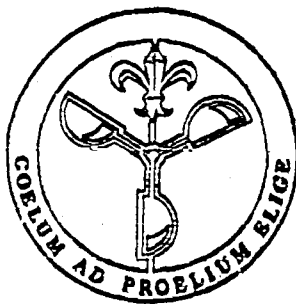
**D E P A R T M E N T   O F   T H E   A I R   F O R C E**

**AWSTR 105-86**

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**TROPOPAUSE ANALYSIS  
AND  
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**MARCH 1952**

**D E P A R T M E N T   O F   T H E   A I R   F O R C E**

## Foreword

1. *Purpose:* Air Weather Service Technical Report No. 105-86, "Tropopause Analysis and Forecasting" is published for the information and guidance of all concerned.

2. *Scope:* This report outlines a recommended procedure of construction of tropopause charts and tropopause prognostic charts for guidance of those forecasting detachments which have a requirement for such charts. A discussion of the basis for the recommendations and illustrative examples are included. These procedures have been developed and tested in Hq. Air Weather Service and are believed to be well adapted for the particular present needs of this Service. They represent a combination of certain ideas proposed in the older literature and new conceptions growing out of recent experience with the expanded upper-air coverage now available.

3. *Supply:* Additional copies of this report may be procured in accordance with provisions of AWS Letter 5-3.

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## Section I. INTRODUCTION

This report is intended as a guide to the construction and analysis of tropopause charts and the construction of prognostic tropopause charts.

The value of tropopause charts is demonstrated in connection with—

- a. Determining the height at which the maximum wind will be found.
- b. Accurate analysis of the temperature field on constant-pressure charts.

- c. Upper level forecasting for air operations.

The applications of tropopause charts in forecasts for other meteorological elements such as cirrus clouds, turbulence, visibility, etc., will be covered in future technical reports and manuals to be prepared when sufficient experience and additional information have accumulated.

## Section II. STRUCTURE OF THE TROPOPAUSE

The tropopause has always been defined simply as the boundary between stratosphere and troposphere. Early ideas of the tropopause held it to be a surface of discontinuity at which there is a marked decrease of lapse rate. Detailed investigations of this boundary with accurate and abundant data have indicated that the tropopause is not so much a single surface as a layer. The term *tropopause layer* has been proposed by Byers (sec. VIII, ref. 3), and by Flohn and Penndorf (Sec. VIII, ref. 7). In this layer the lapse rate changes from its tropospheric value to its stratospheric value by either a single change toward greater stability (*surface of stabilization*) or by successive steps, giving either a single or *multiple tropopause*. The multiple tropopauses are often in evidence in the vertical cross sections as an *overlapping leaf-like structure*. The tropopause layer is generally found at high elevations and low temperatures in the low latitudes and at low elevations and relatively high temperatures in high latitudes. The potential temperature in the tropopause layer is far from constant laterally, being highest in low latitudes and lowest in high latitudes. The greatest changes of height, temperature, and potential temperature of the tropopause

layer are usually found in the vicinity of strong wind currents in the high troposphere.

The leaf-like structure of the tropopause has been studied in detail by Palmén (sec. VIII, ref. 9), and Bjerknes and Palmén (sec. VIII, ref. 2). They found that each one of the tropopause surfaces in a "bundle" or layer is characterized by a relatively constant potential temperature, although its height varies. With the aid of a series of "swarm ascents" of balloon meteorographs they tabulated the changing values in space and time for the various tropopause surfaces at several stations. Their table for Ås in Norway is reproduced as an illustration (see table 1).

The mean values of potential temperature for each of the four tropopause surfaces observed at Ås for the 3-day period are—

I	II	III	IV
294	306	315	328

The same tropopauses appeared in soundings from adjacent stations for the same time.

Palmén (sec. VIII, ref. 9) demonstrated that the variations of the tropopause layer in time and space are accomplished by the

TABLE 1. Analysis of the Tropopause in the Ascents at *As*, Feb 1932.

(From Markers and Palmden)

ASCENTS	(Surface I)			(Surface II)			(Surface III)			(Surface IV)		
	dyn km	° C	T	dyn km	° C	T	dyn km	° C	T	dyn km	° C	T
15 0709	7.39	-55	296									
1507	6.92	-51	294									
1600	6.45	-48	293									
1805	6.59	-48	294	8.25	-53	303						
2001							9.35	-53	318			
2200				8.32	-63	297						
2400				8.25	-53	303						
0200				8.20	-56	304						
0300				8.44	-56	308						
0400				8.47	-59	305						
0600				8.24	-53	303						
0707				8.36	-56	306						
1600				8.70	-53	309				10.24	-63	328
2000				8.15	-54	307	8.85	-56	314			
2100				8.11	-54	306	8.87	-56	314			
2200				8.00	-62	307	8.59	-55	311			
2300				8.09	-55	305						
2400				8.00	-51	309						
0200				7.97	-54	305						
0400				8.22	-55	307						
0600				8.58	-56	310						
1005				8.38	-54	309						
1600							9.70	-62	316			
1800							9.82	-65	314			






disappearance of some individual *tropopause leaves* and the appearance of others. This fact has also been demonstrated in many later studies, for example by Bjerknes and Palmén (sec. VIII, ref. 2), Bémont et al., (sec. VIII, ref. 1), and Graves (sec. VIII,

ref. 8), and is amply supported by recent synoptic experience.

Palmén (sec. VIII, ref. 9) and Flohn and Penndorf (sec. VIII, ref. 7) give three main types of tropopause structure, shown in table 2.

TABLE 2. *Tropopause Types.*

TROPOPAUSE TYPE	CHARACTERISTIC TEMPERATURE-HEIGHT CURVE	CHARACTERISTIC WEATHER SITUATIONS
1. NORMAL TYPE		STATIONARY WEATHER SITUATION
2. LIFTING TYPE		WARM-AIR ADVECTION, WARM-AIR ANTICYCLOGENESIS
3. SUBSIDENCE TYPE		TROPOSPHERIC COLD-AIR ADVECTION; CORE OF STATIONARY LOW

The three types represent an oversimplified classification of the diverse lapse-rate curves encountered in the atmosphere but are useful in relating tropopause structure to atmospheric processes.

Under certain conditions at high latitudes, the recognition of a tropopause becomes very difficult. Occasionally a lapse-rate curve will be observed where there are nearly

isothermal conditions prevailing from the ground to the top of the sounding. At other times there will be a slight but relatively steady decrease of temperature upward through the whole sounding (see Court (sec. VIII, ref. 5)). In either case the tropopause is a matter of arbitrary definition. In the latter case, one might say that there is no tropopause at all.

### Section III. DEFINITION OF THE TROPOPAUSE

When the lapse rate changes from its tropospheric value to its stratospheric value by a single change towards greater stability, the tropopause is taken to be identical with this surface of stabilization. If there are several tropopause leaves, or *points of stabilization*, in a sounding, the question of

tropopause definition is more difficult. Due to the desirability of representing the tropopause structure on a single map, it has been found convenient to define a *predominant tropopause* in such a way as to give maximum usefulness to the single tropopause chart.

Aviation requirements for the tropopause chart vary from year to year, and it is not possible to predict future requirements with accuracy. During the last few years, meteorologists have come to regard the most important characteristic of the tropopause as its association with the *maximum-wind in the vertical*. In view of this, six different definitions of a predominant tropopause have been studied in an effort to determine their suitability with respect to giving the best "fit" to the maximum-wind in the vertical. The best definition appears to be as

follows: *The predominant tropopause is found at the lowest point in the sounding where the lapse rate decreases to  $2^{\circ}$  C. per kilometer of pressure altitude or less, and averages  $2^{\circ}$  C. per kilometer or less for the first two kilometers of pressure altitude<sup>1</sup> above the point of stabilization (frontal and other middle—or low—tropospheric stable layers excepted).*

<sup>1</sup> Pressure altitude is used as a height unit throughout this report unless otherwise specified in order to eliminate a large number of height computations and due to its suitability for use in forecasts for aviation.

#### Section IV. RELATION OF TROPOPAUSE HEIGHT TO THE HEIGHT OF MAXIMUM-WIND

The relation of the predominant tropopause, as defined above, to the height of the maximum-wind is shown in figures 1a, 1b, 1c, which were compiled from all available rawinsonde data from the United States and its Caribbean stations for 1950.

The results from all the data are shown in figure 1a, indicating that the maximum-wind in the vertical is found most frequently just below the predominant tropopause. There is, however, a considerable spread of the individual tropopause-height values about the most frequent (modal) height, due to the inclusion of all values regardless of wind speed, location of the station, or type of tropopause. (The spread of values about the modal height is significantly reduced if only cases of high winds are examined).

In figure 1b the data are shown after separation into different latitude belts. Below  $30^{\circ}$  N. the maximum wind is found about 8 km below the tropopause, with a relatively small number of maximum-wind observations at the tropopause, in agreement with a recent study by Colón (sec. VIII, ref. 4). (The failure of Colón's wind-maximum above the tropopause to appear in figure 1b

is probably due to the small number of wind ascents reaching very high levels.) The frequency graph for the stations north of  $40^{\circ}$  N. shows a much better-developed maximum in the first kilometer below the tropopause. The diagram for the belt  $30-39^{\circ}$  N. apparently shows a combination of the distributions for lower and higher latitudes.

When the data are separated according to the tropopause types of table 2, results are obtained as shown in figure 1c. For tropopauses of type I or type II, the maximum-wind is found close to the tropopause. For tropopauses of type III, the maximum-wind occurs most frequently about 2 km below the tropopause, possibly in association with the occurrence of lower secondary tropopauses in this type of situation. However, caution must be exercised in the use of tropopause types, since many soundings do not conform well to any of the commonly accepted types. Also the type of tropopause observed often depends on how high the sounding extends. Therefore, the practice of typing tropopauses should be limited to studies of a statistical nature and is not recommended for daily analysis work.

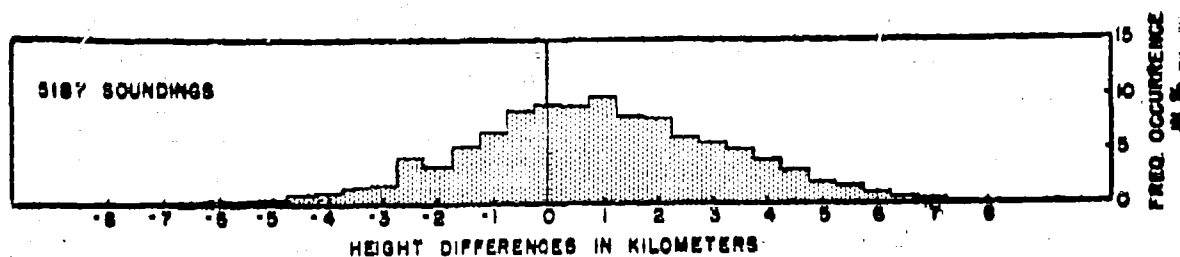


FIGURE 1a. Frequency Distribution of Height Differences: height of tropopause minus height of maximum wind. Data for all stations, all seasons, and all tropopause types are included.

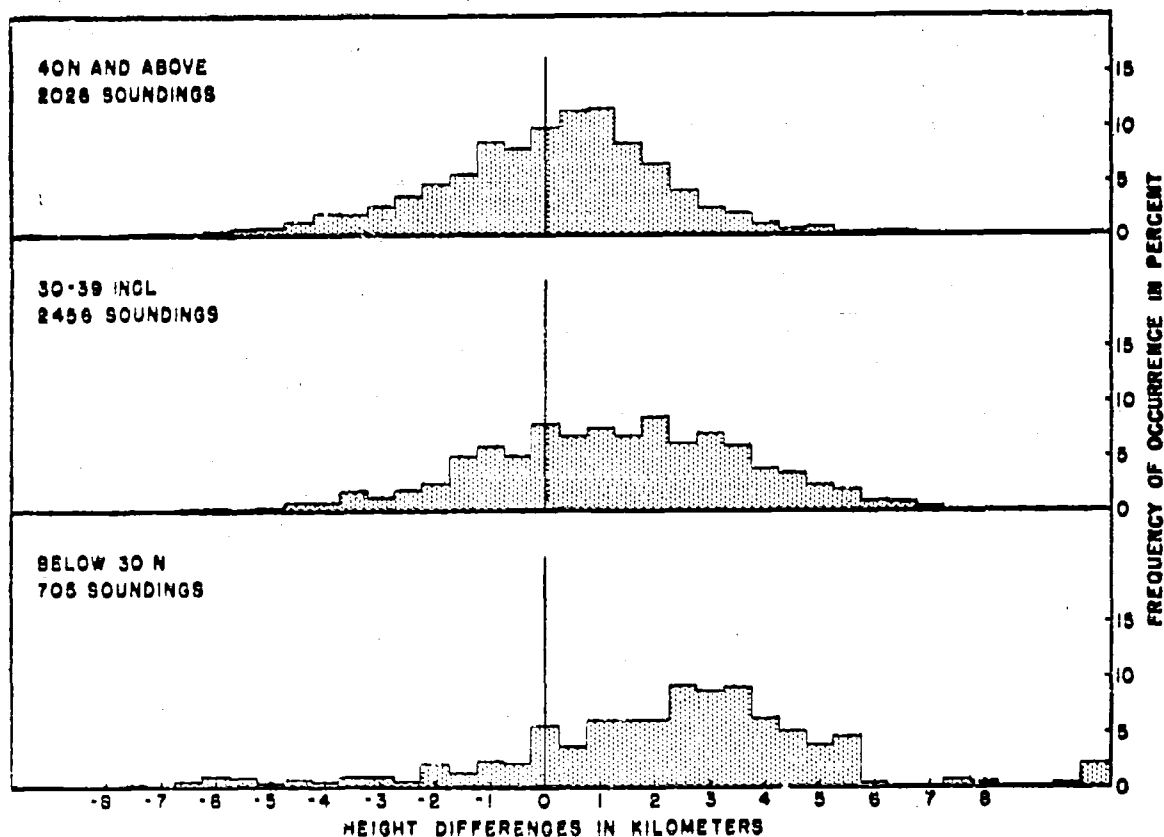


FIGURE 1b. Same Data as in Fig. 1a but the data have been sub-divided according to latitude belts.

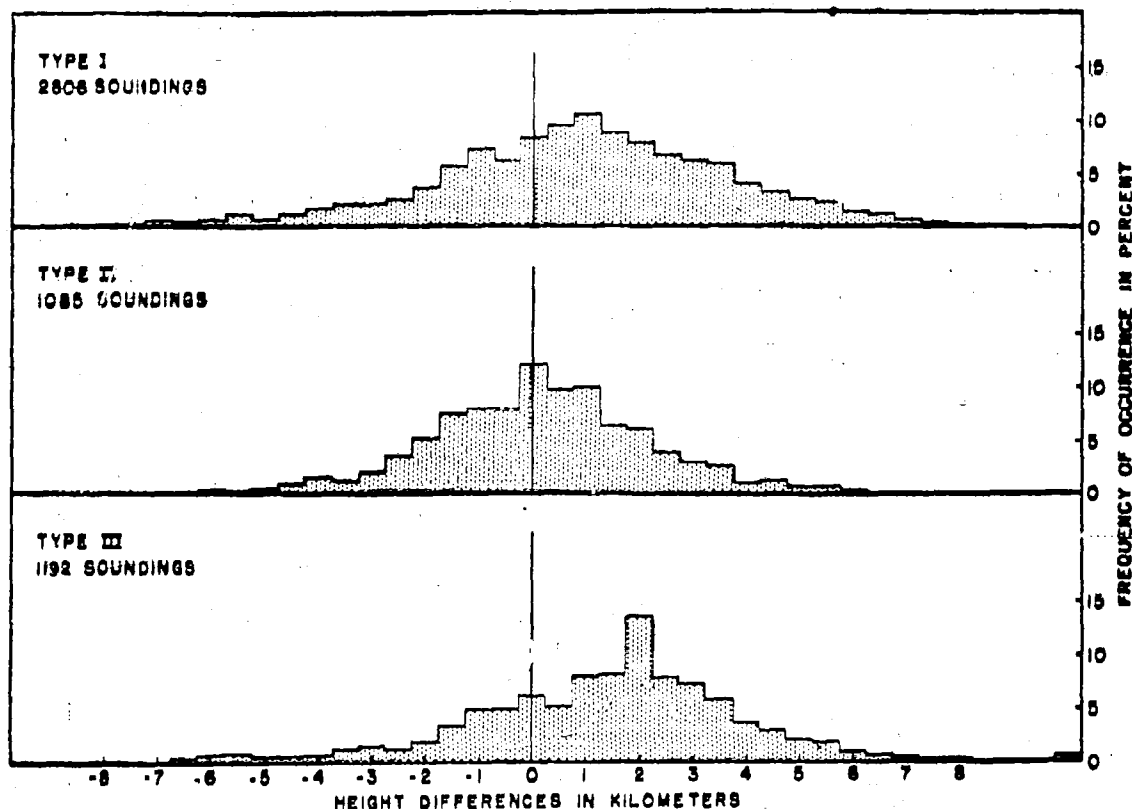


FIGURE 1c. Same Data as in Figure 1a but Grouped According to the Tropopause Types Given in Table 2.

## Section V. CHOOSING A METHOD OF TROPOPAUSE ANALYSIS

Owing to its complicated structure, the tropopause presents a difficult analysis problem. A method of tropopause analysis should serve several purposes, as follows:

1. It should enable the analyst to determine the general distribution in space of the boundary between troposphere and stratosphere.

2. It should give the location in the vertical of pronounced changes in hydrostatic stability. This information is significant for determination of:

- a. The elevation at which the large-scale meridional temperature gradient reverses and therefore the elevation at which the maximum-wind in the vertical is found, since the strong changes in horizontal tem-

perature gradient in the tropopause layer are associated with sloping surfaces of stabilization.

- b. The location of contrails, upper haze layers, cirrus clouds and turbulence.

3. The method of analysis used should be simple enough to permit a generalized forecast of the above features.

Requirements 1 and 3, and to a certain extent requirement 2 can be satisfied by the analysis of a chart of the predominant tropopause. Such a chart will show the geographical distribution of the tropopause layer, from which the approximate geographical distribution of the maximum-wind in the vertical is inferred. Also it has been demonstrated that the height of the predominant

tropopause can be forecast for a 24-hour period with a skill significantly greater than persistence.

Major interruptions of the tropopause involving elevation changes of as much as 20,000 feet or more can occur in certain places, particularly in the vicinity of strong wind-maxima in the horizontal (jet streams) (for example, see Riehl (sec. VIII, ref. 12) or Palmén and Nagler (sec. VIII, ref. 10)). It seems desirable to show these major breaks on the tropopause chart (an analysis including all the smaller breaks would present an unduly complicated picture). Con-

tinuous tropopause contours can be drawn in the region between the major breaks.

A chart of the predominant tropopause, however useful, falls in certain respects. Potential temperature, although conserved in space and time along the individual tropopause leaves, is not necessarily constant along the predominant tropopause. A plotting of the intersections of the predominant tropopause with constant-pressure surfaces will not aid the analyst in an analysis of the temperature field. The details of the several surfaces of stabilization, or leaves, can not be readily shown on a single chart.

## Section VI. TROPOPAUSE ANALYSIS

A fairly complete tropopause analysis can be obtained as follows:

1. A Tropopause Chart is plotted. Potential temperature and pressure for each stabilization surface at each station are plotted on a map. The particular point corresponding to the definition of the predominant tropopause is indicated by a symbol (e.g., underlining). In the event that a large number of stabilization points is observed on a particular sounding, it is advisable in the interest of simplicity to limit the number of points plotted to three—the predominant tropopause and the nearest stabilization point above and below it.

2. The pressure (or pressure-altitude) values of the predominant tropopause are analyzed. Since it is not possible to forecast details of the tropopause, this serves as the basic type of prognostic as well as analyzed tropopause chart. The forecast tropopause is useful in this form for determining the height at which the maximum wind will be found in the future.

3. The intersections of each leaf are entered on the appropriate constant-pressure surfaces. Since each leaf is characterized by nearly constant potential temperature, its intersection will be characterized by a corresponding temperature. This fact aids in an accurate analysis of the temperature field on the constant-pressure surfaces.

*Analyzing the Tropopause Chart.* In the analysis of the tropopause chart, one needs to consider the plotted values for the predominant tropopause, which are obtained by the procedure described above. The analysis is usually made in terms of pressure altitude as mentioned earlier, for convenience in translating the analysis into a description or forecast for aircraft operations. A 3,000-foot contour interval is sufficient to give a good description of the tropopause.

Since tropopause interruptions or breaks of many sizes can be observed in the data, some sort of selection is desirable. The entering of all the breaks which could be found would result in a chart which would be too complicated to use. On the other hand if no breaks were entered on the chart, the drawing of elevation lines would be very difficult in places where the tropopause height differs by 15,000 feet or more at adjacent stations. A criterion for tropopause breaks which does not lead to inconvenient complications is to draw a break only where the difference in potential temperature of the tropopause between adjacent radiosonde stations exceeds 15 to 20 degrees. The more extensive breaks thus obtained will usually parallel the direction of high-tropospheric flow, and will often be found

in close proximity to wind-speed maxima in the horizontal.

Portig (sec. VIII, ref. 11), following the type of statistical analysis first made by Dines (sec. VIII, ref. 6) and by Schedler (sec. VIII, ref. 13), has shown the correlation between height of the tropopause and the pressure at various levels at Munich, figure 2. (Many similar studies are available in the literature.) The relations given by a graph of this type can be used in a general way to check the tropopause analysis, particularly in areas where data are missing. One expects to find a high tropopause associated with upper-air ridges or highs, and a low tropopause associated with upper-air troughs or lows. This simple and well-known principle will often serve to avert inconsistencies in the analysis.

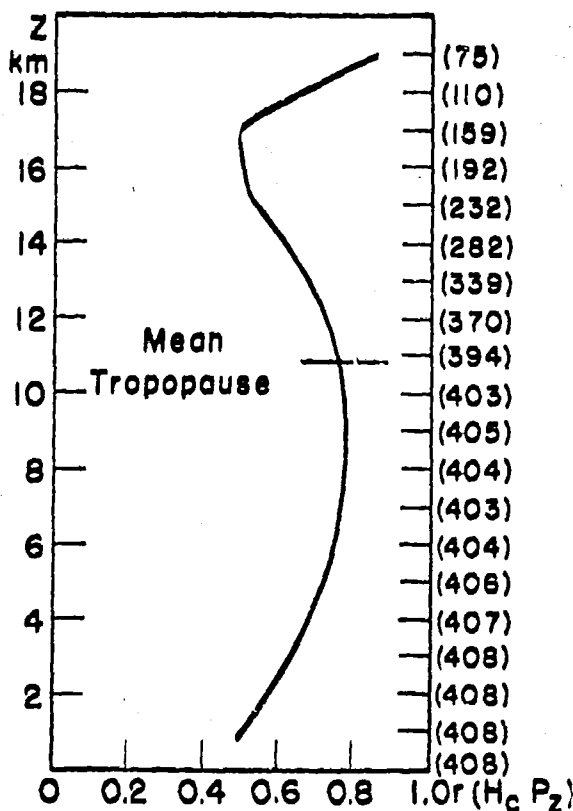


FIGURE 2. Correlation coefficient ( $r$ ) between the air pressure ( $P_s$ ) at the surface and the height ( $H_s$ ) of the tropopause at Munich as a function of height. The numbers in parentheses are the number of ascents reaching the given level. (After Portig)

*Examples.* An example of tropopause analysis is shown with accompanying 500-mb charts in figures 3a, 3b, 3c, 3d, 3e, 3f. In order to eliminate unnecessary detail only the data for the predominant tropopause points are plotted on the tropopause charts. The problem of intersections with constant-pressure surfaces will be discussed in the next section.

Broadly speaking the tropopause over the United States in this example can be divided into three general sections. The most extensive section is characterized by potential temperatures of from approximately  $55^\circ\text{C}$ . to  $75^\circ\text{C}$ . and is located near 200 mb (38,700 ft. pressure altitude). A second section, lying north of the maximum-wind (from the 500-mb chart), is characterized by potential temperatures of from  $35^\circ\text{C}$ . to  $45^\circ\text{C}$ . and is located near 300 mb (50,100 ft. pressure altitude). A third section appears over Florida on 21 March and moves northward during the following 24 hours. This is a characteristic *tropical tropopause* with temperatures of from  $-75^\circ\text{C}$ . to  $-80^\circ\text{C}$ . and potential temperatures near  $120^\circ\text{C}$ ., located a little below 100 mb (53,200 ft. pressure altitude). There are two principal *break-lines* between these general sections. The break between the middle and lower tropopause sections conforms approximately to the maximum-wind at 500 mb. The southern break corresponds to a secondary wind maximum in the horizontal, which is located along the Gulf Coast of the United States. This maximum is somewhat more prominent at 200 mb than at 500 mb.

In the major ridge, where the 500-mb wind-maximum is much weaker, there is no abrupt or pronounced change in elevation of the tropopause such as can be found near pronounced jet streams. Since the tropopause breaks depend to a certain extent on the strength of the wind at the core of the jet stream, it is to be expected that a break-line will not extend interminably across the map, but will gradually disappear towards regions of weak wind.

On 20 March, the tropopause is low in the region of the major trough at 500 mb and over the tropospheric cold air mass. An

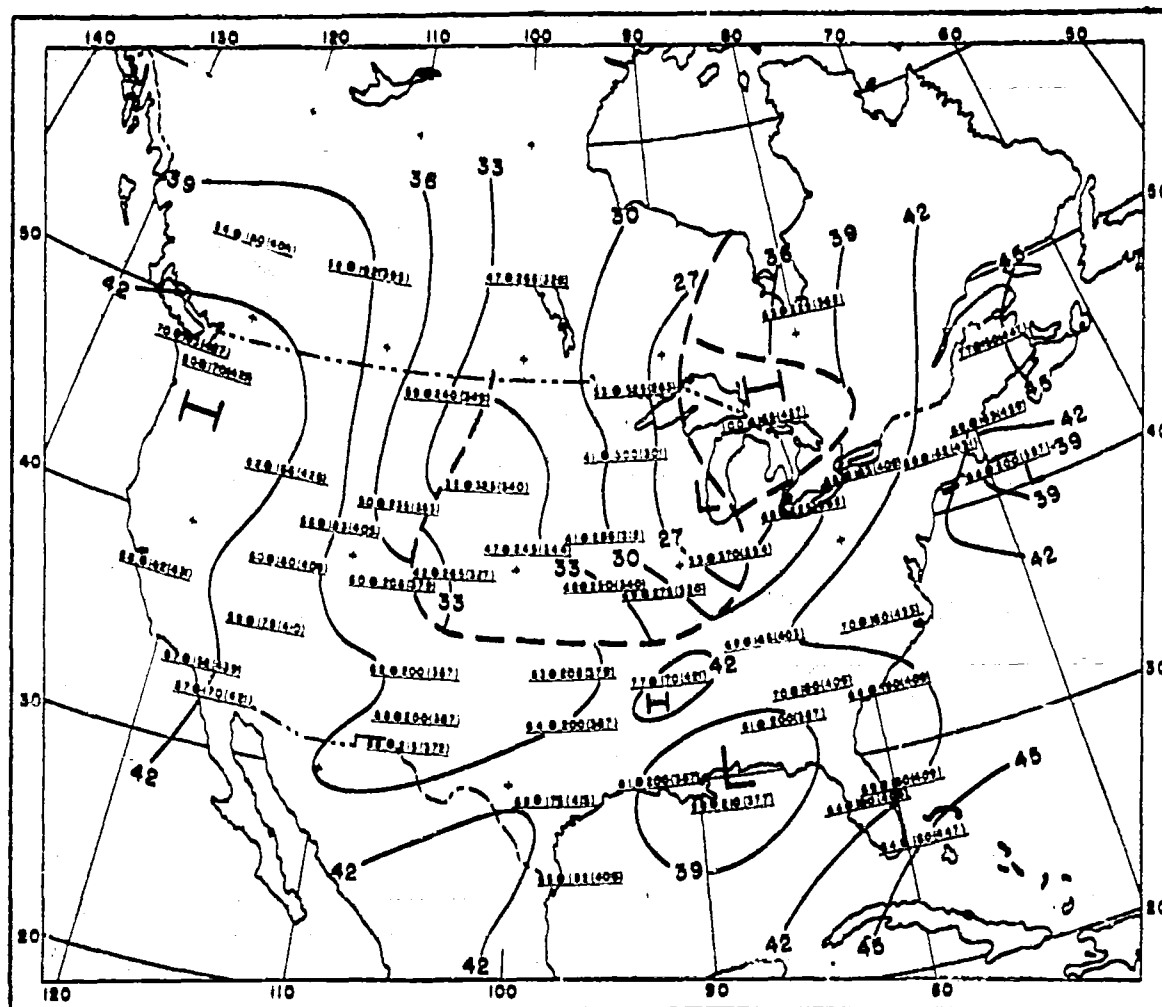


FIGURE 8a. Tropopause Chart for 0800 GCT, 20 March 1951. Only the data for the predominant tropopause are reproduced (underlined). The potential temperature of the tropopause in degrees centigrade is plotted to the left of the station circle and the pressure of the tropopause in millibars is plotted to the right. The pressure altitude of the tropopause in hundreds of feet is in parentheses. The contours are drawn in three-thousand foot intervals, solid lines, last two digits omitted. Break-lines are indicated by the heavy dashed lines.

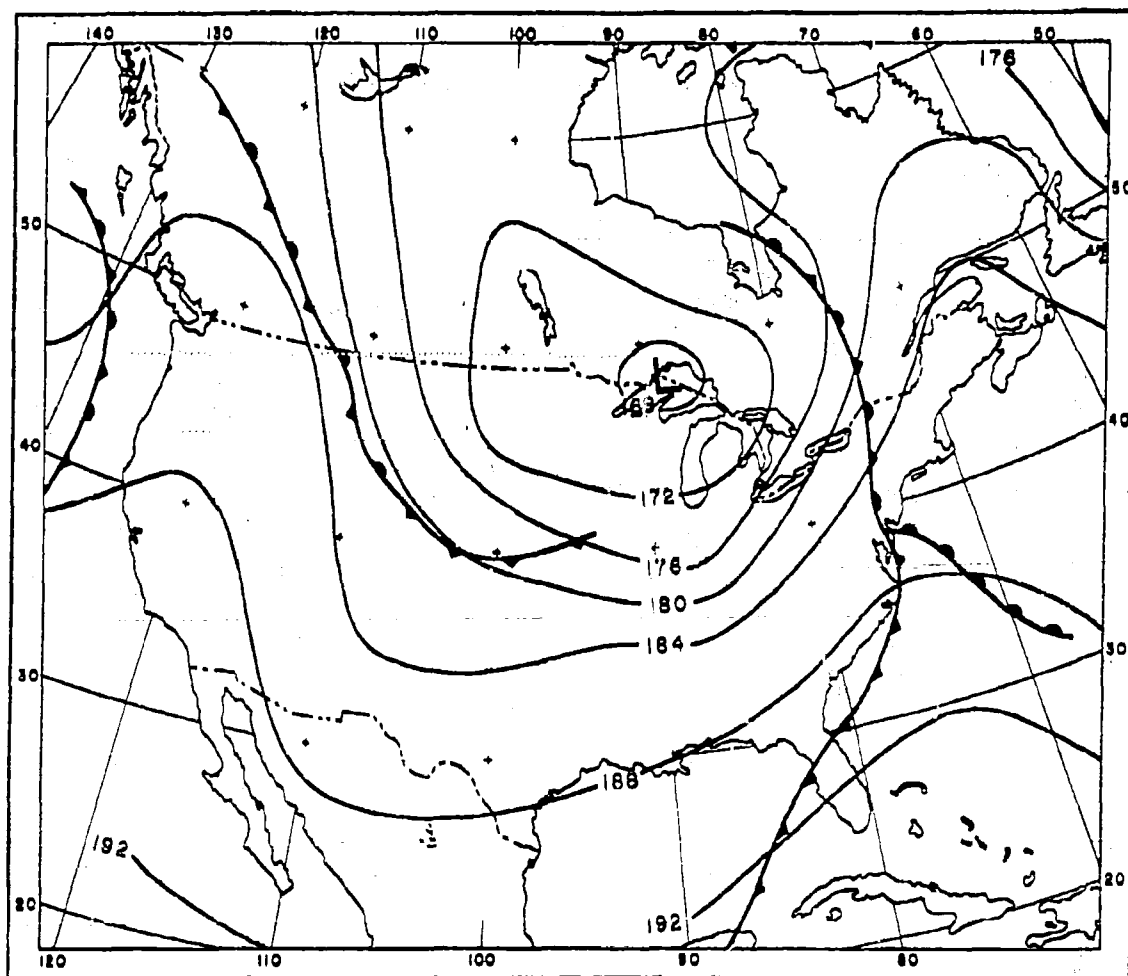


FIGURE 8b. 500-mb Chart with Superimposed Surface Fronts, for 0300 GCT, 20 March 1951.





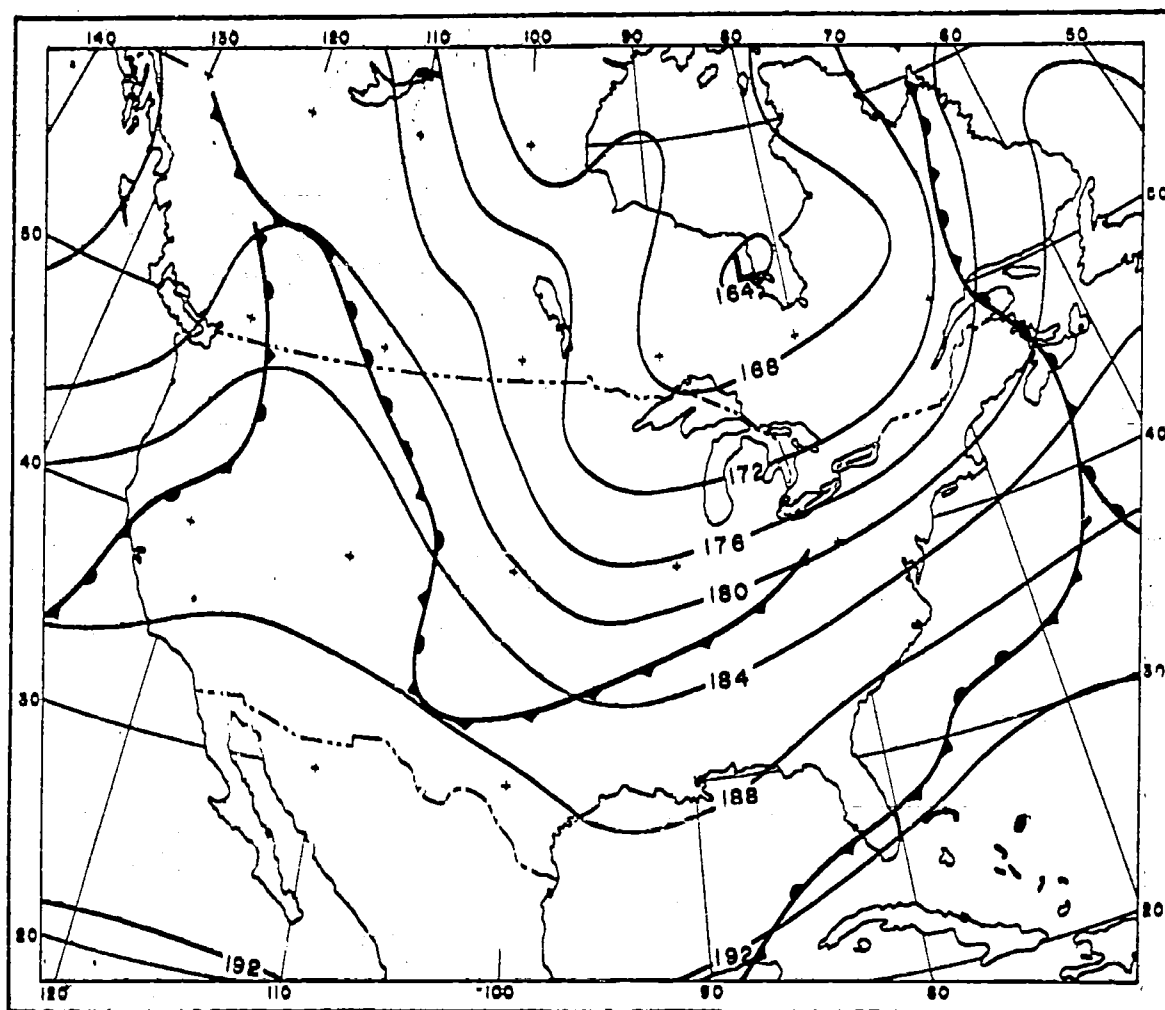


FIGURE 8d. 500-mb Chart with Superimposed Surface Fronts, for 0300 GCT, 21 March 1951.

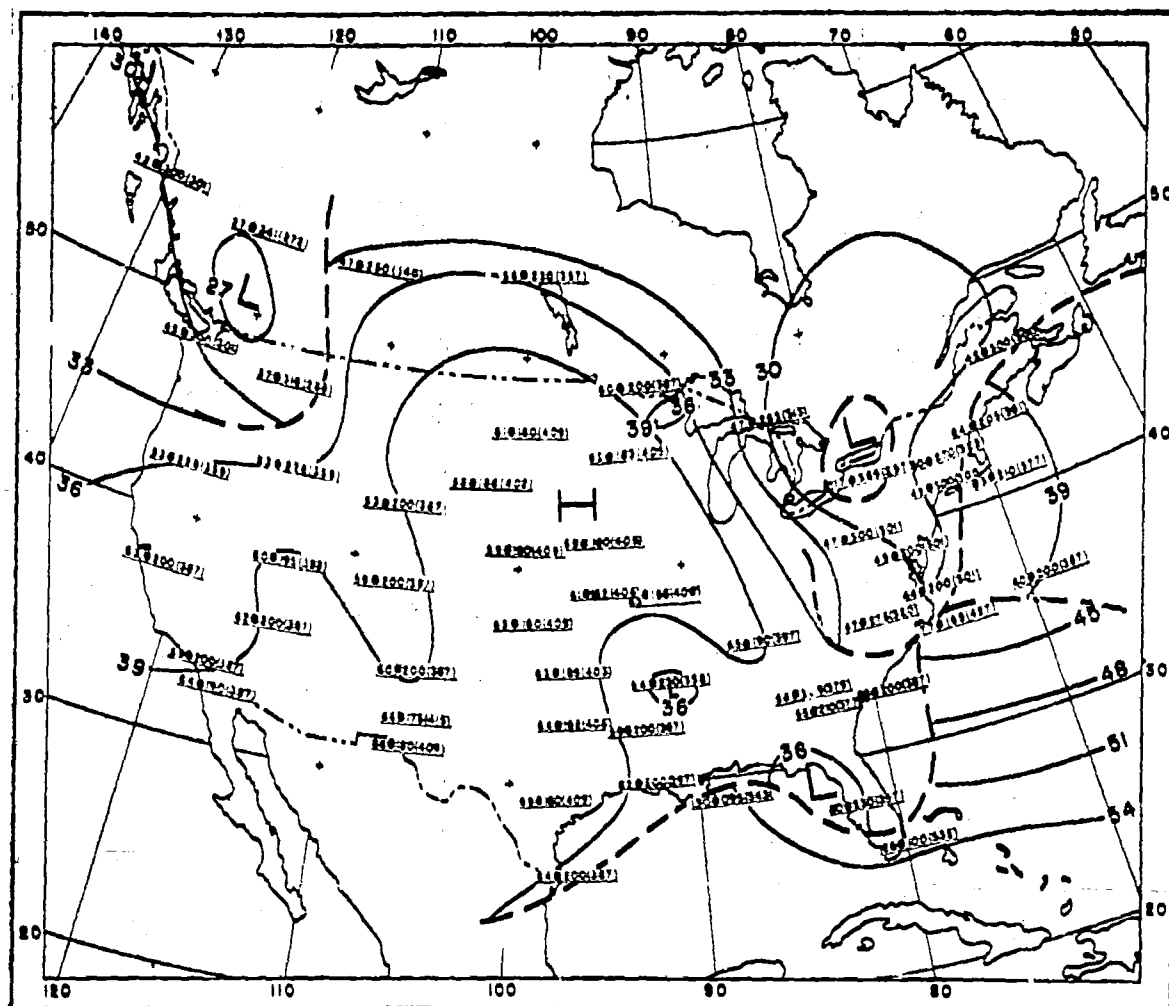


FIGURE 8e. Tropopause Chart for 0200 GCT, 22 March 1951.

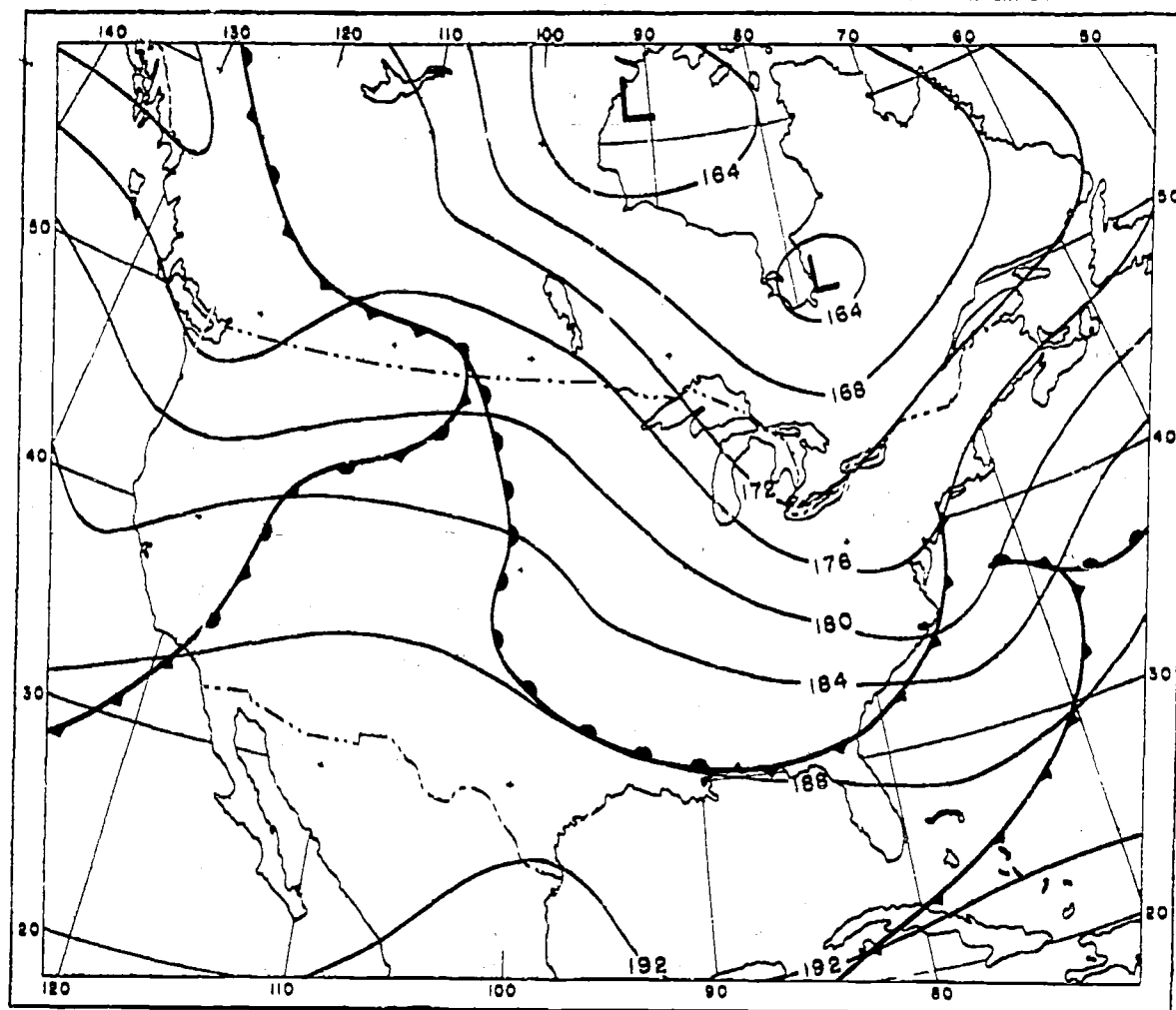


FIGURE 8f. 500-mb Chart with Superimposed Surface Fronts, for 0300 GCT, 22 March 1951.

interesting feature is the small area of very high tropopause over the Great Lakes. This area does not appear on the maps for the following two days, possibly due to insufficient data. The region of low tropopause moves eastward with the major trough during the next 2 days. On 22 March a very low tropopause is reported at Buffalo, N. Y., and at the same time a very high tropopause at Hatteras, N. C. This difference of 17,000 feet pressure altitude in the tropopause at these stations is associated with an intensification of the major trough at 500 mb and with the beginning of low-level cyclogenesis off the east coast of North America.

In the vicinity of the 500-mb major ridge the tropopause is high and flat. It is characterized throughout the 8-day period by a remarkably constant potential temperature of about  $62^{\circ}\text{C}$ ., indicating that only one surface of stabilization is involved here.

Another area of low tropopause moves in over the northwest part of the map on 22 March 1951, following a fresh low-level cold air outbreak in that area and in association with another major trough at 500 mb.

In figure 4, the details of the tropopause structure over part of the map on 22 March 1951 are shown by the upper portions of the soundings for four stations.

At Swan Island several stabilization points are shown, with a pronounced tropopause leaf at a potential temperature of  $127^{\circ}\text{C}$ . This same leaf marks the point of minimum temperature on both the Brownsville and Burrwood soundings. A weakening of this leaf toward the north is shown by comparing these soundings with the Dodge City sounding. On the three northern soundings a lower tropopause leaf characterized by potential temperatures near  $65^{\circ}\text{C}$ . is indicated. Although this leaf does not appear at Swan Island and is weak at Burrwood, it is pronounced at Brownsville and coincides with the minimum temperature at Dodge City. The break at which the lower tropopause became predominant, was drawn therefore just north of Burrwood and just south of Brownsville. However, there was not a sharp break in the tropopause, but rather a broad overlapping of two tropo-

pause leaves, each leaf being characterized by a nearly constant potential temperature. The representation of such a zone as a break-line is justified by the necessity for maintaining a simple and feasible procedure.

In contrast to the above case, we can examine a situation in which the predominant tropopause slopes gradually. Such a situation is shown in figure 5.

Here there is a stabilization point on all three soundings at a potential temperature of  $59^{\circ}\text{C}$ . At Nantucket this is the lower of two tropopause surfaces. At Albany, it is pronounced, and is the only tropopause present. At Rome, the  $59^{\circ}\text{C}$ . surface is the higher of two equally pronounced tropopause leaves, which are relatively close together. The tropopause chart therefore shows the predominant tropopause sloping continuously down toward the westnorthwest.

A third type of situation is found in the vicinity of the major ridge. The soundings in figure 6 from three widely-separated stations on 21 March 1951, show the same well-developed tropopause surface, which is found over a large area. Although the temperature in this tropopause varies considerably, the potential temperature is very nearly constant.

*Intersections of the Tropopause with Constant-Pressure Surfaces.* At the present time the analysis of the tropopause intersections with constant-pressure surfaces appears to have its chief value as an aid in the drawing of isotherms on the constant-pressure charts. The basic principle of this application is illustrated in figures 7a-c.

Figure 7a is a section of a tropopause chart on which the potential temperature and pressure at the tropopause are shown for four stations, A, B, C, and D. The solid line indicates the intersection of the tropopause with the 200-mb surface. Figure 7b is a vertical cross section from A to C. An abrupt change of the gradient of potential temperature (and consequently of temperature) on the 200-mb surface is clearly revealed. The 200-mb chart for the same area as the tropopause chart (7a) is shown in figure 7c. Without knowledge of the tropopause intersection, one would ordinarily

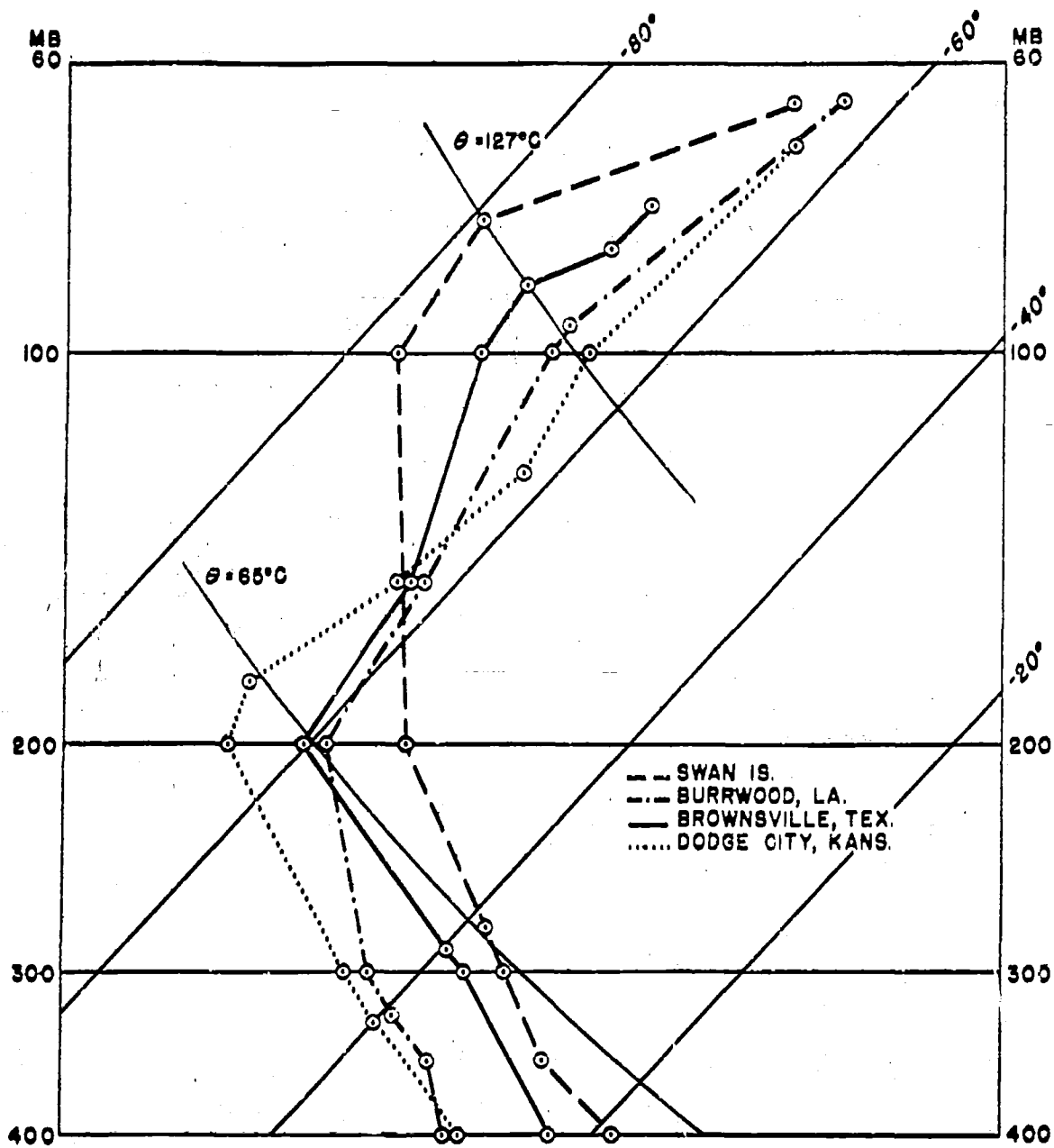


FIGURE 4. Selected Soundings for 0800 GCT, 22 March 1951 (On Skew T—Log P Diagram)

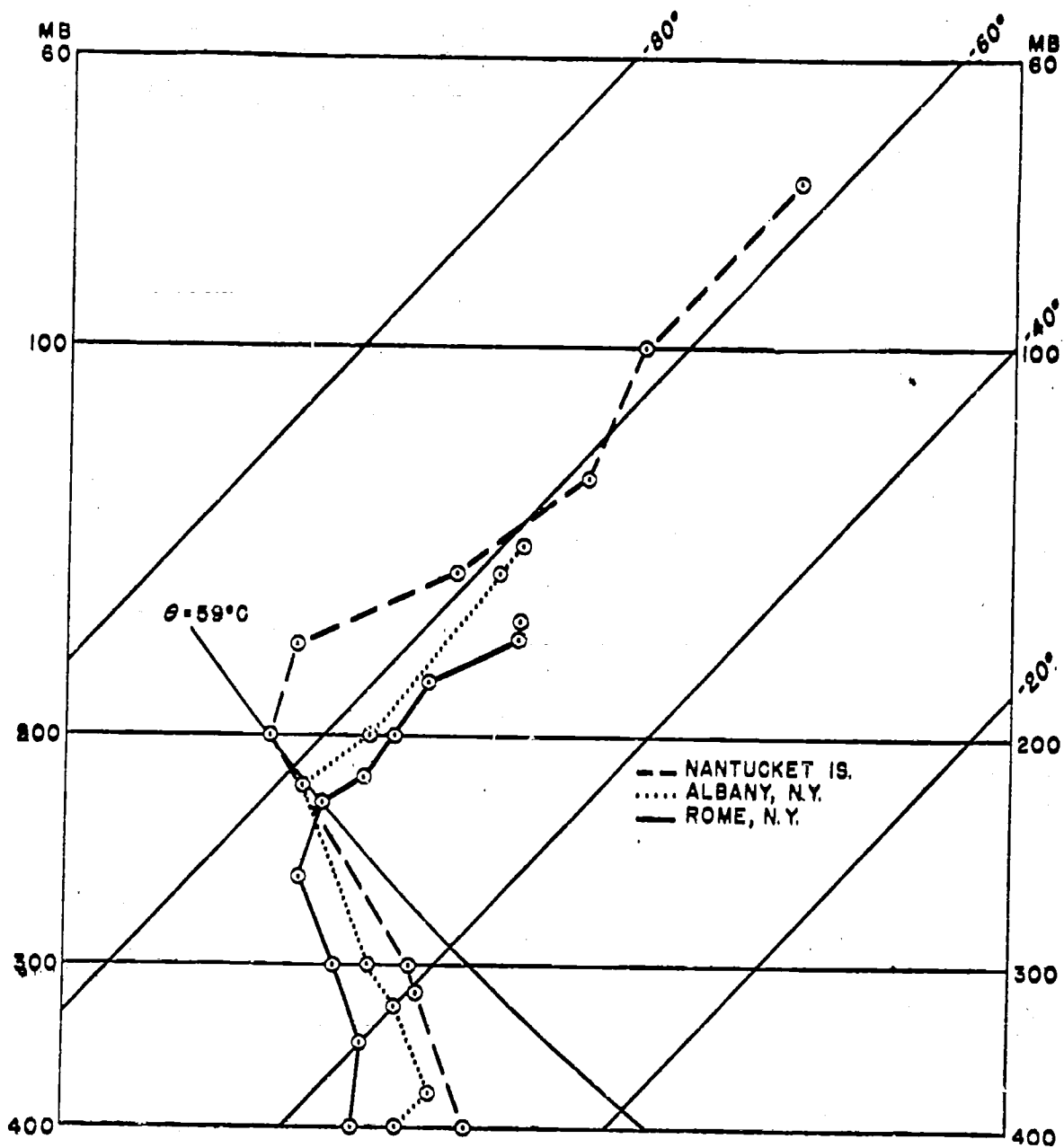


FIGURE 5. Selected Soundings for 0300 GCT, 31 March 1951.

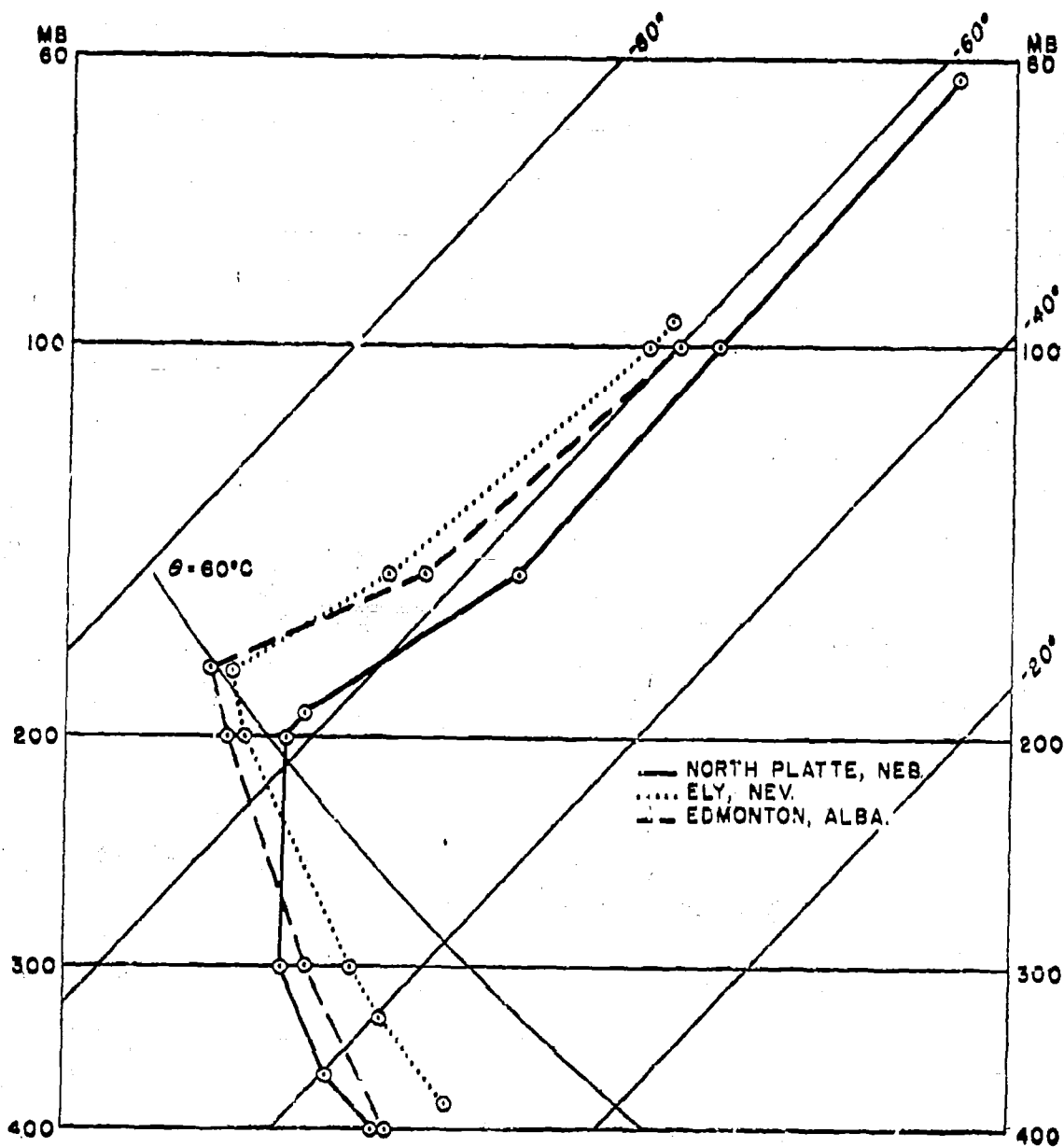


FIGURE 6. Selected Soundings for 0300 GCT, 21 March 1981.



space the isotherms evenly between the stations. However, the tropopause intersection, obtained from the tropopause chart in figure 7a, is characterized by a potential temperature of  $80^{\circ}\text{C}$ ., which corresponds to a tem-

perature of  $-63^{\circ}\text{C}$ . at 200 mb. A much better picture of the 200-mb isotherms is then obtained by accepting the tropopause intersection as the  $-63^{\circ}\text{C}$ . isotherm, which leads to different temperature gradients

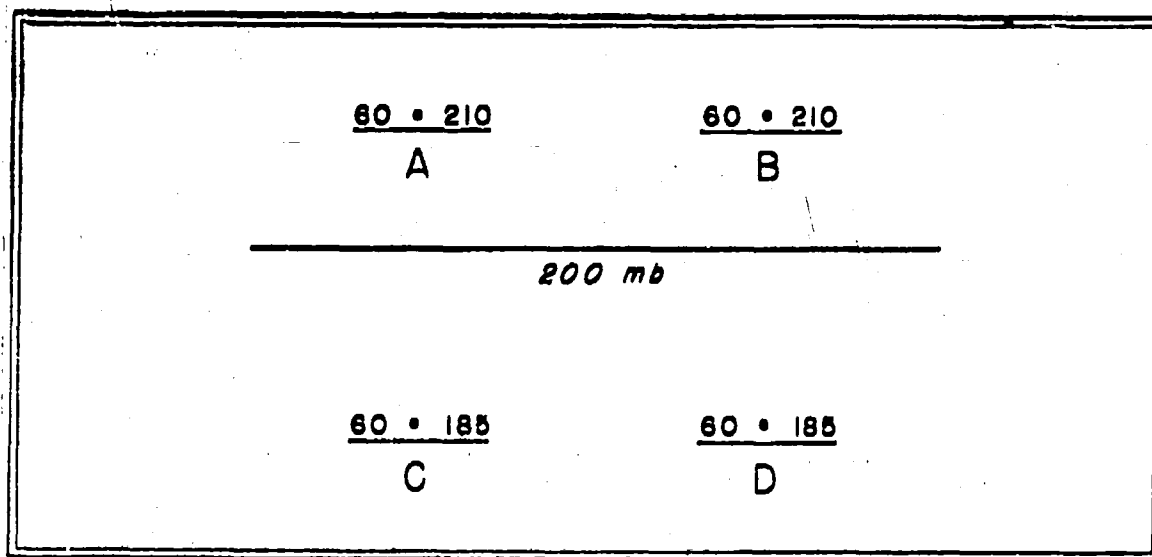


FIGURE 7a. Potential Temperature and Pressure of the Tropopause Surface Plotted on a Tropopause Chart. The 200-mb isobar on the tropopause surface has been entered.

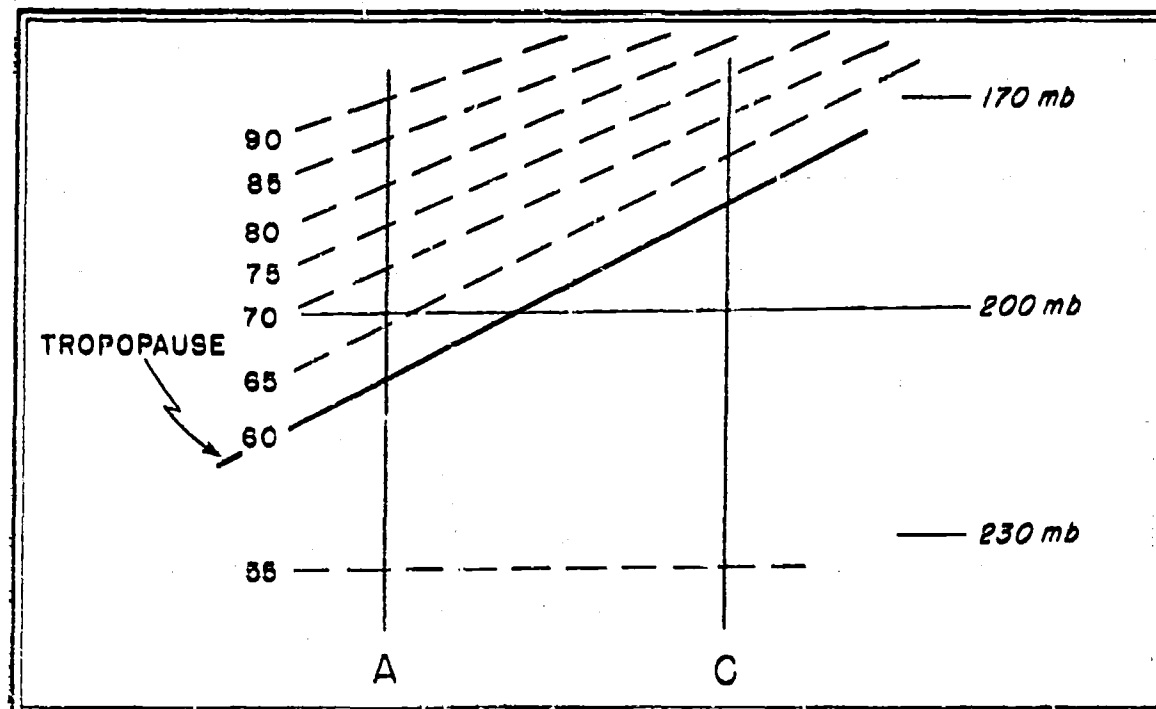


FIGURE 7b. Vertical Cross-Section from A to C. Dashed lines are isentropic surfaces. The heavy line is the tropopause.

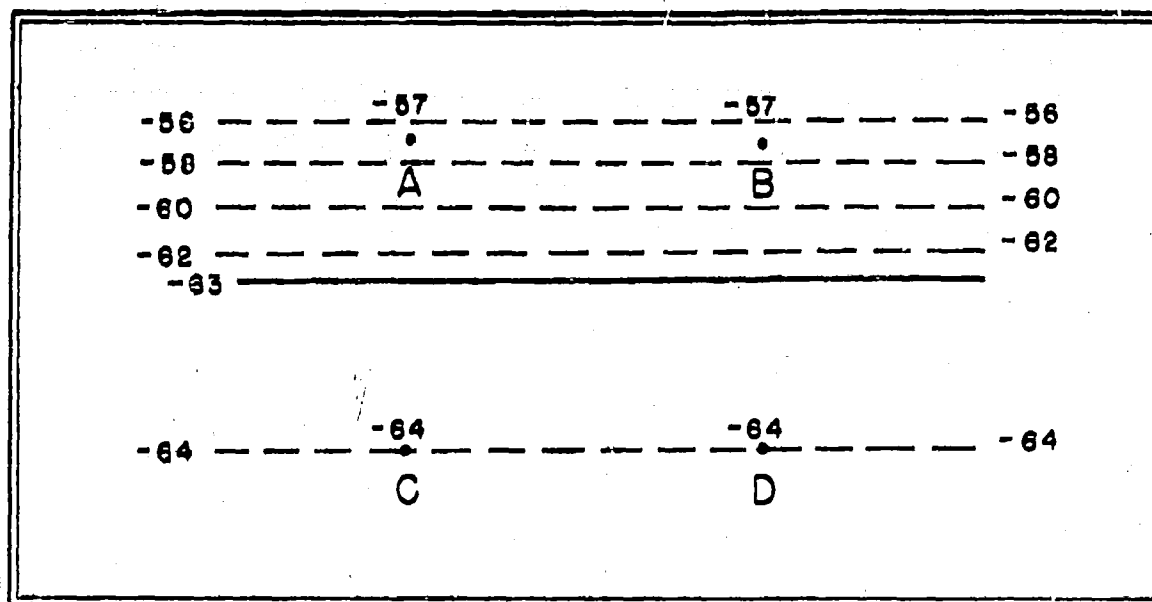


FIGURE 7c. Tropopause and Temperature Analysis at 200-mb.  
The heavy line is the tropopause intersection.

Example Showing the Intersection of Two Tropopause Leaves  
with the 200-mb Surface (Figures 8a-8c).

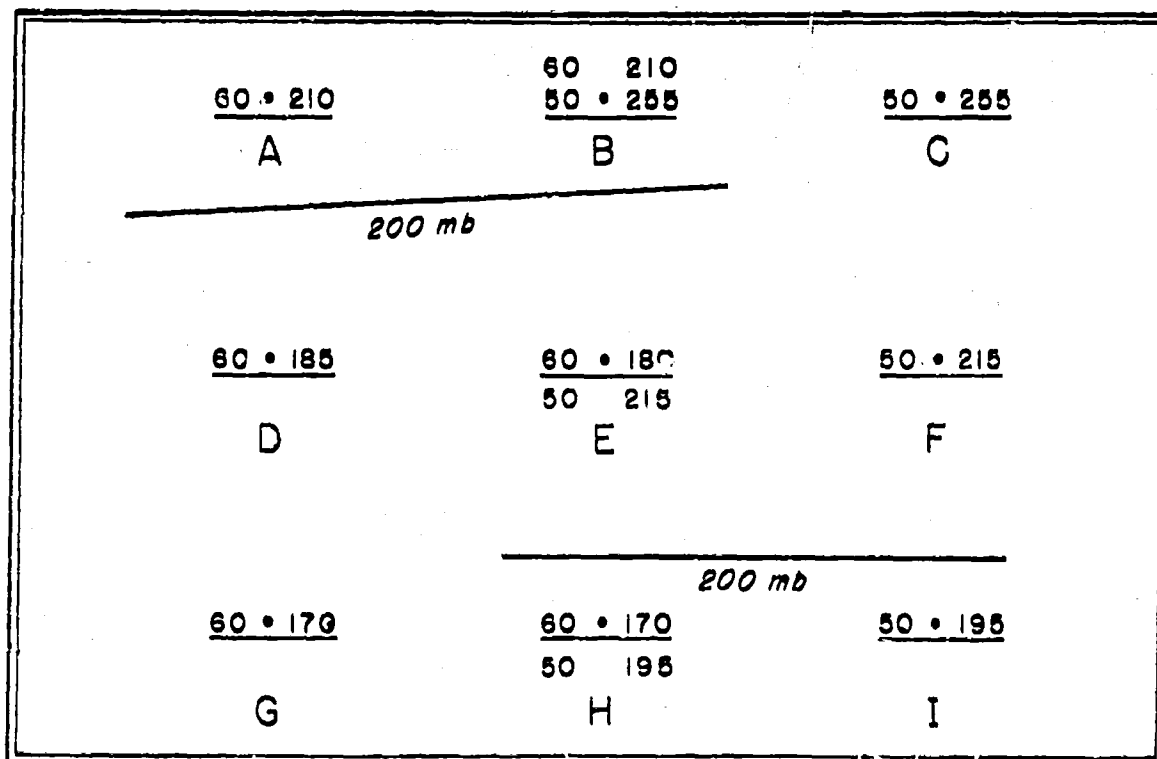


FIGURE 8a. Potential Temperature and Pressure of the Tropopause Leaves Plotted on a Tropopause Chart.  
Values for the predominant tropopause are underlined. The 200-mb isobar on each leaf has been entered.

north and south of the tropopause, as indicated in the cross section.

A more complicated example is shown in figures 8a-c.

The tropopause chart for this situation, figure 8a, indicates two separate leaves of the tropopause, characterized by potential temperatures of  $50^{\circ}\text{C}$ . and  $60^{\circ}\text{C}$ . These surfaces of stabilization are shown as overlapping leaves in the vertical cross-section through stations B, E, and H, figure 8b. The 200-mb intersections of these two leaves are obtained from figure 8a, and transferred to the 200-mb chart, figure 8c. They are characterized by temperatures of  $-63^{\circ}\text{C}$ . and  $-69^{\circ}\text{C}$ . at 200 mb. The resulting 200-mb isotherm picture is fixed by the reported 200-mb temperatures and by the temperatures corresponding to the tropopause intersections. It is interesting to note that an aircraft flying at 200 mb from G to E to C could pass from troposphere to stratosphere without penetrating a tropopause. An actual situation in which this could be done oc-

curred in the southern U. S. on 22 March 1951, as shown by the soundings in figure 4. Here a flight from south to north at 150 mb would give the desired result.

The above examples, although slightly idealized, illustrate a use of the general principle that the intersections of the tropopause surfaces (leaves) with constant-pressure surfaces are characterized by nearly constant potential temperatures and consequently by nearly constant temperature. On a constant-pressure surface isotherms can extend from troposphere to stratosphere: (a) by crossing tropopause leaves at wide intervals, or (b) more commonly by extending between intersections of individual leaves, as shown in figure 8.

A situation frequently is seen where an extensive tropopause break-line is found between tropopause leaves which do not intersect a constant-pressure surface, e. g., 200 mb, similar to the 22 March 1951 analysis shown in figures 8e and 4.

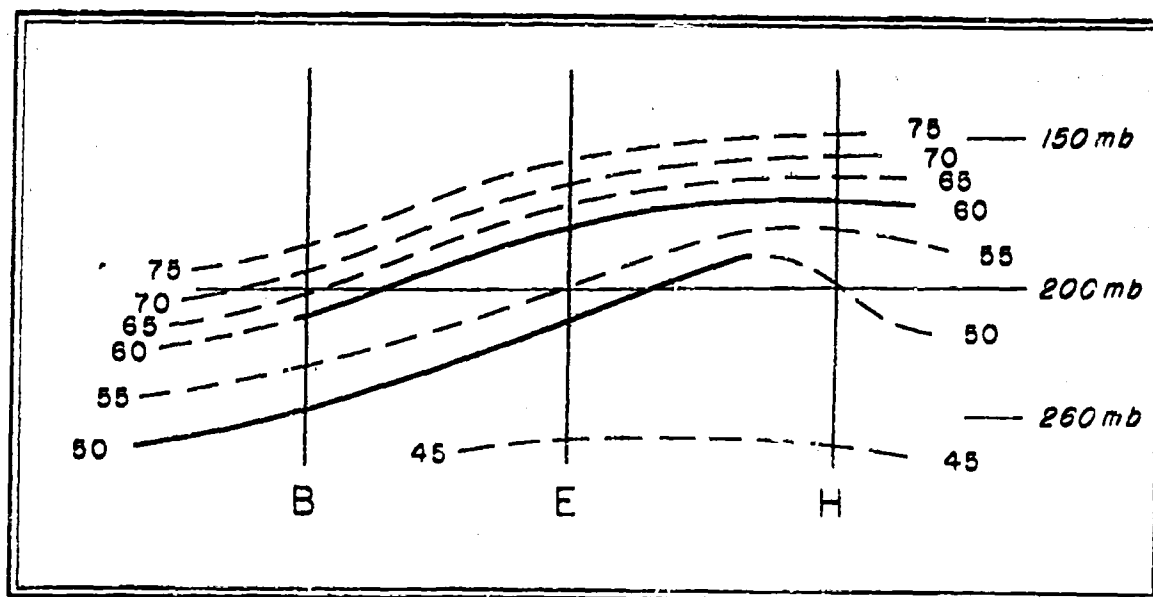


FIGURE 8b. Vertical Cross-Section from B to E to H. Dashed lines are isentropic surfaces. Heavy lines are the tropopause leaves.

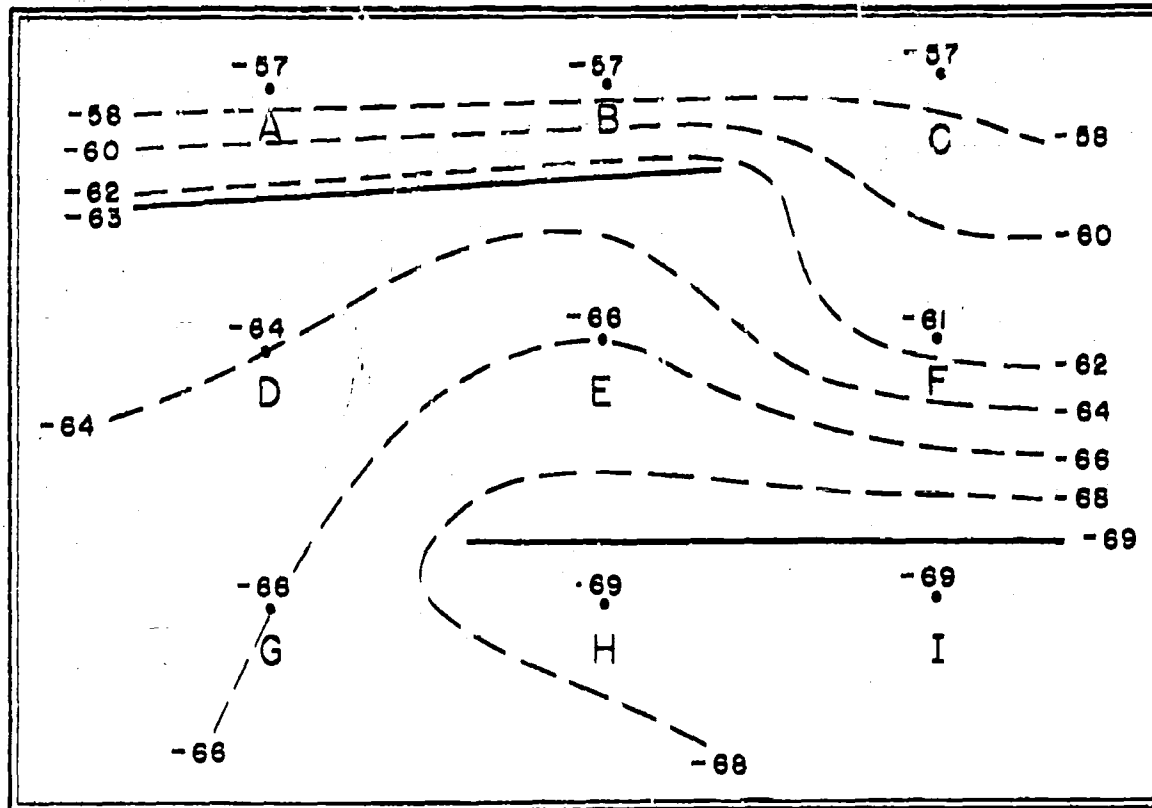


FIGURE 8c. Tropopause and Temperature Analysis at 200-mb. The heavy lines are the intersections of the separate tropopause leaves.

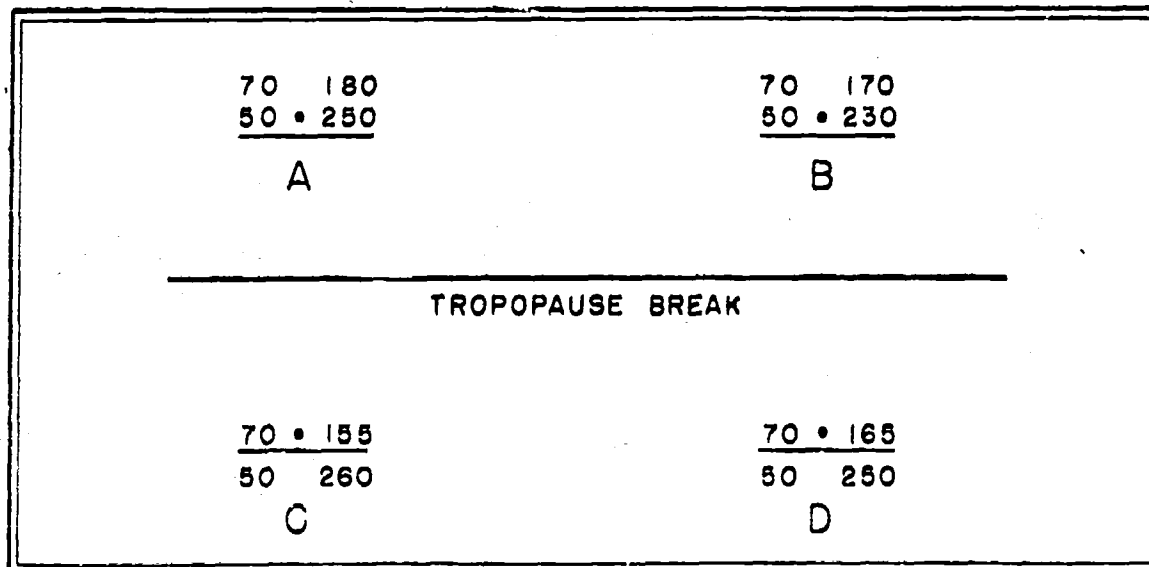


FIGURE 9a. Tropopause Data for Four Stations Plotted on a Tropopause Chart. The heavy line is the tropopause break-line.

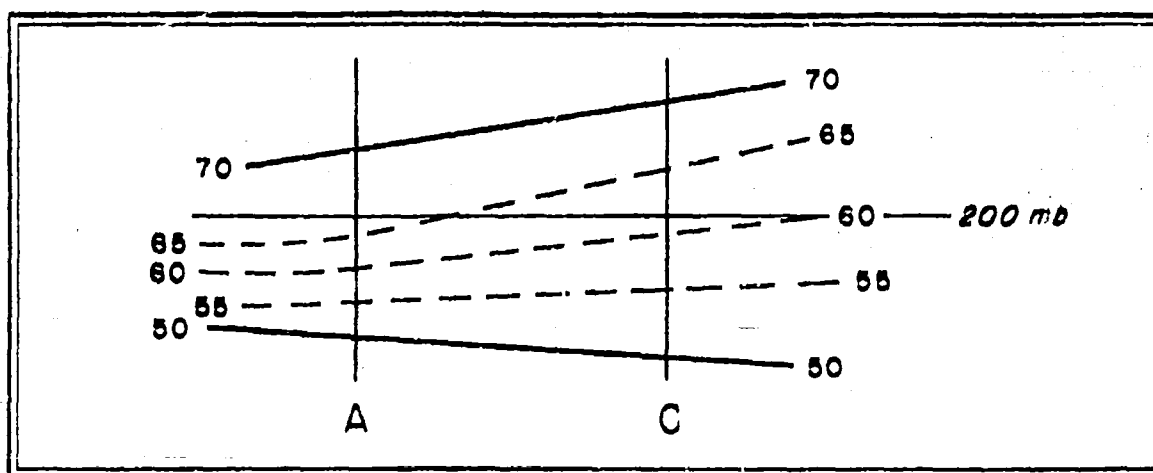


FIGURE 9b. Vertical Cross-Section from A to C. Dashed lines are isentropic surfaces. Heavy lines are the tropopause levels.

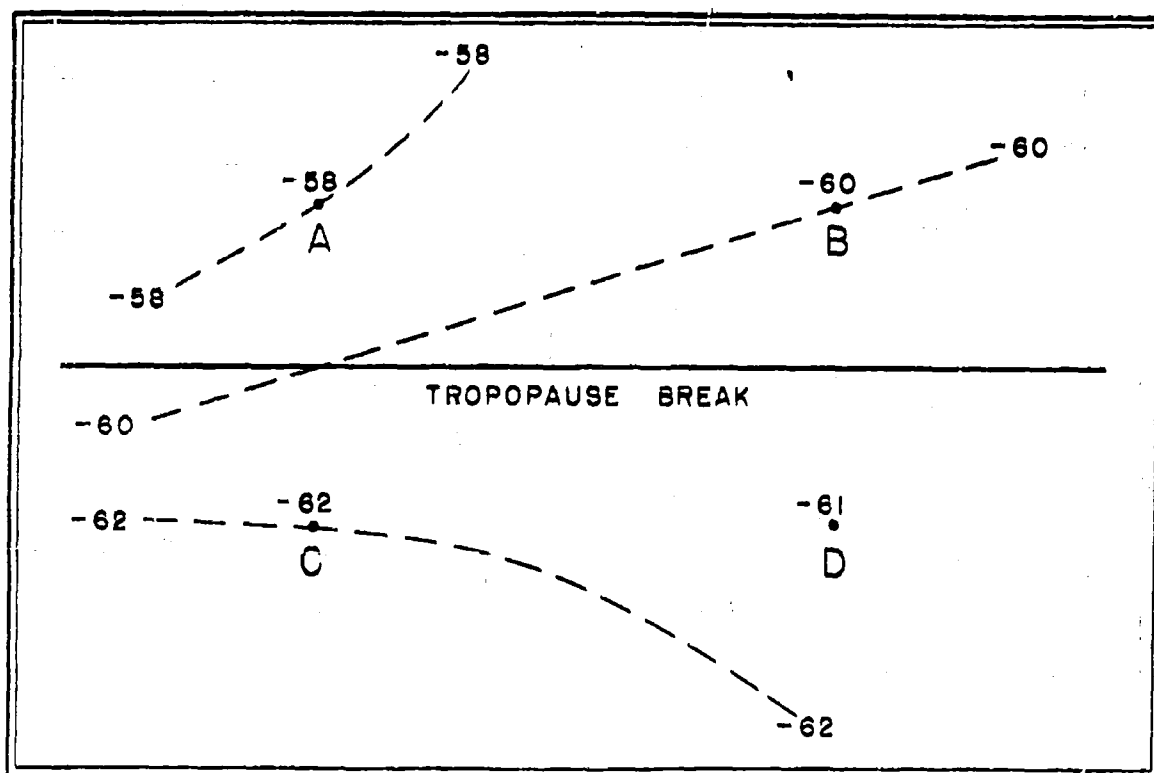


FIGURE 9c. Tropopause and Temperature Analysis at 200-mb. The heavy line indicates the tropopause break.

This type of situation is also shown in figure 9a where the tropopause data for four stations is shown, together with a break-line. This corresponds to the cross section shown

in figure 9b. According to the definition of the predominant tropopause given earlier, 200 millibars at stations A and B is in the stratosphere, while at stations C and D it is

in the troposphere. The resulting temperature analysis at 200 millibars is shown in figure 9c.

The entering of the break-line on the 200-mb chart from the tropopause chart is merely a matter of convention, and has no value for the temperature analysis. In this type of situation the isotherm analysis has no relation to the line separating stratosphere from troposphere on the constant-pressure surface.

A final example of tropopause analysis is shown in figures 10a-f in order to illustrate the tropopause intersections with successive

constant-pressure surfaces and their relation to the isotherms. The complete tropopause chart is shown in figure 10a. The high-level flow pattern for the same time is illustrated by the 200-mb contours in figure 10b, and the tropopause intersections and isotherms on the successive constant-pressure charts from 400 mb to 150 mb are given in figures 10c, 10d, 10e, and 10f.

The 400-mb and 150-mb charts represent the two extremes of tropopause height for most of the map. At several places in the northeastern States the tropopause is found as low as, but not lower than, 400 mb. The

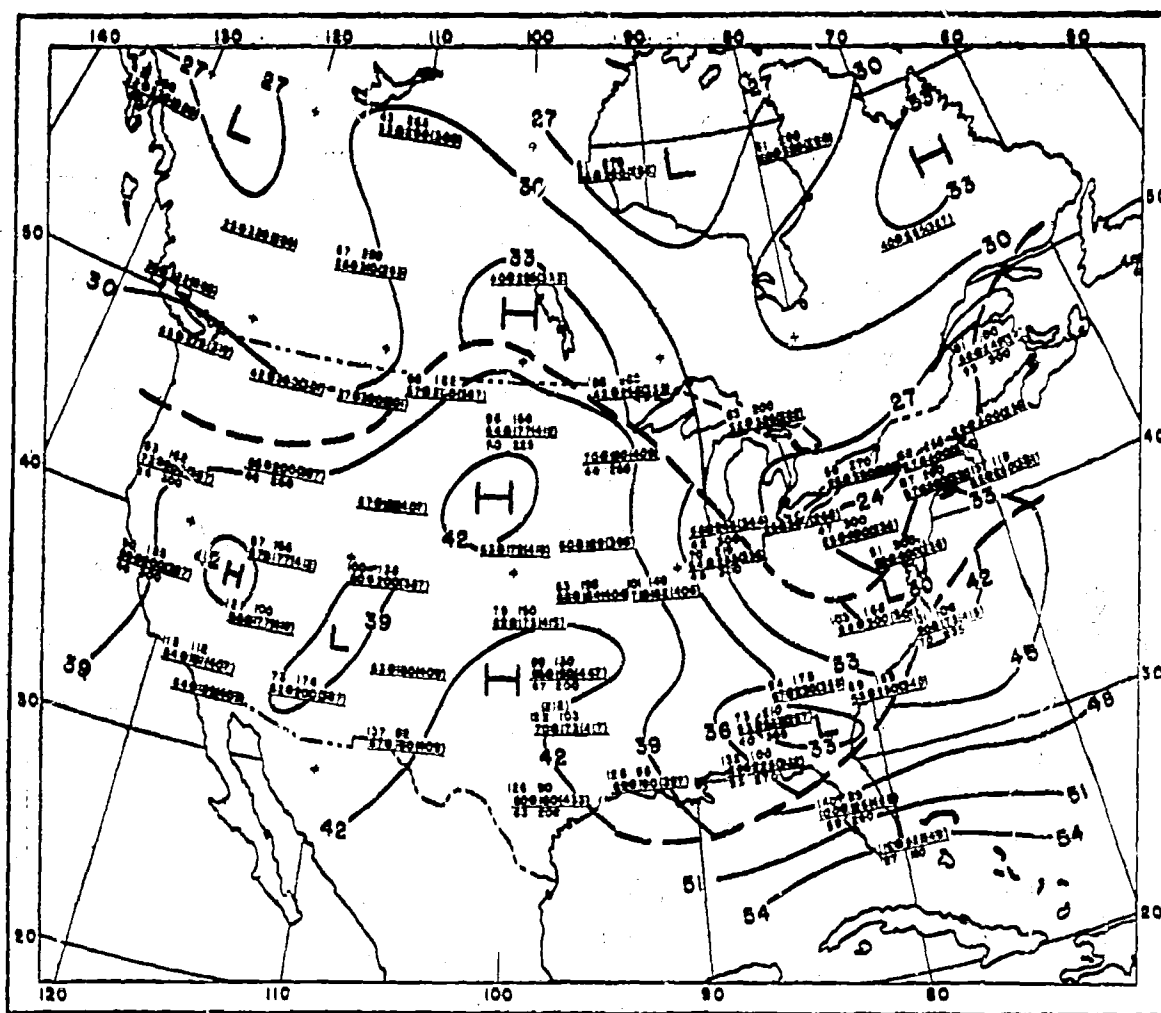


FIGURE 10a. Tropopause Chart for 0300 GCT, 16 Jan. 1951. Plotting model is the same as in Figure 3 except that the potential temperature and pressure of secondary tropopause leaves are entered as well as the values for the predominant tropopause, which are underlined.

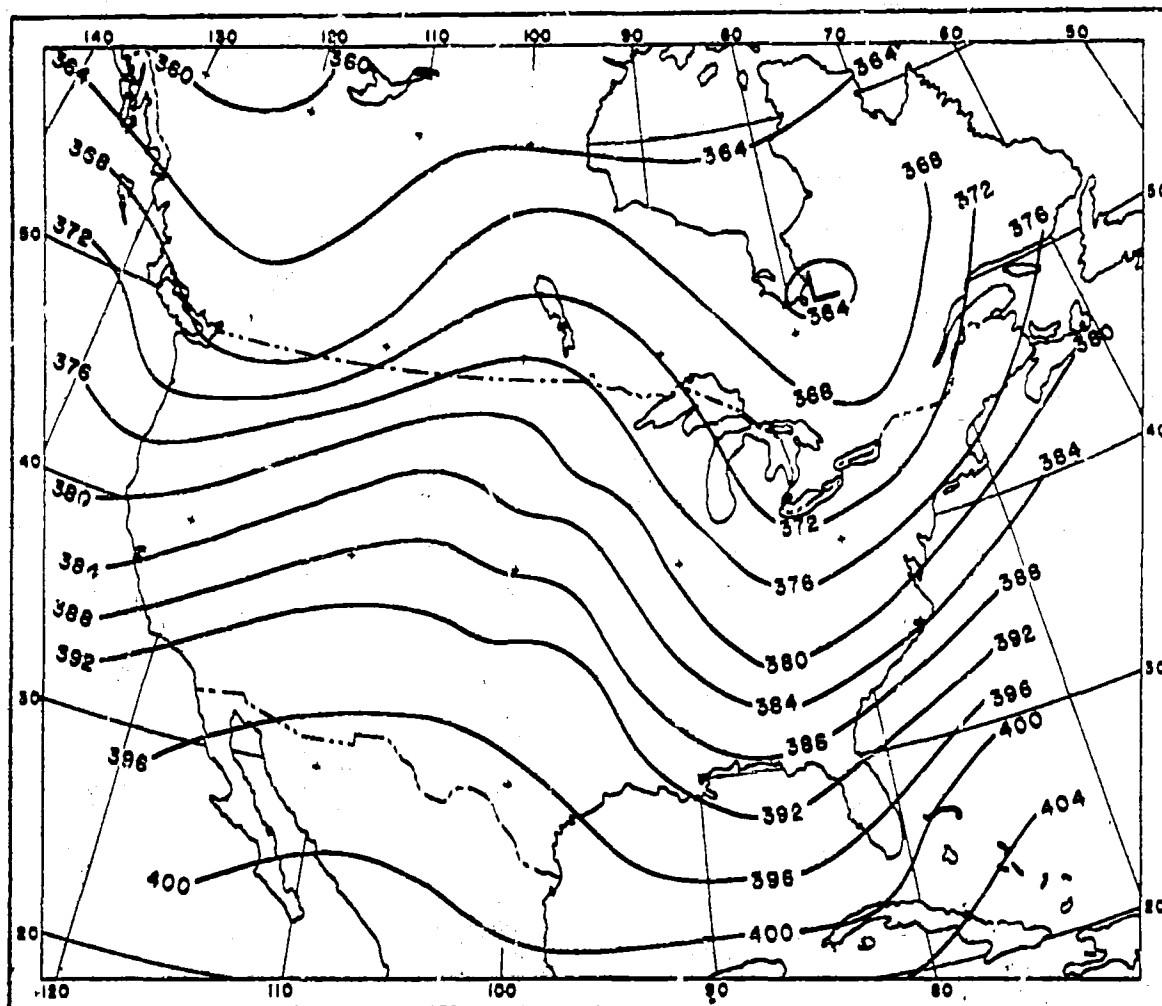


FIGURE 10b. 200-mb Contours for 0800 GCT, 16 January 1961.

400-mb chart is then the highest constant-pressure surface which lies entirely in the troposphere on this date. Here one can see the typical tropospheric pattern of isotherms nearly parallel to the flow pattern with a warm ridge, a cold trough, and temperatures in general decreasing northward. With the exception of part of Florida, the highest point on the tropopause chart is at 150 mb at Oklahoma City. The 150-mb chart is therefore completely in the stratosphere over nearly all of the map. The isotherms here tend to parallel those at 400 mb, but with an oppositely directed gradient, cold temperatures being in the south and warm tempera-

tures in the north, giving a cold ridge and a warm trough.

Occasionally forecasters attempt to analyze the tropopause intersections with constant-pressure surfaces from the horizontal temperature field alone, by drawing the intersections through lines of minimum temperature. The 150-mb chart from this series illustrates the fallacy of this approach. There is a line of minimum temperature extending from Little Rock, Ark., through Ely, Nev. This is associated not with a tropopause intersection, but with a general region of high tropopause well below the chart, at about 180-200 mb.

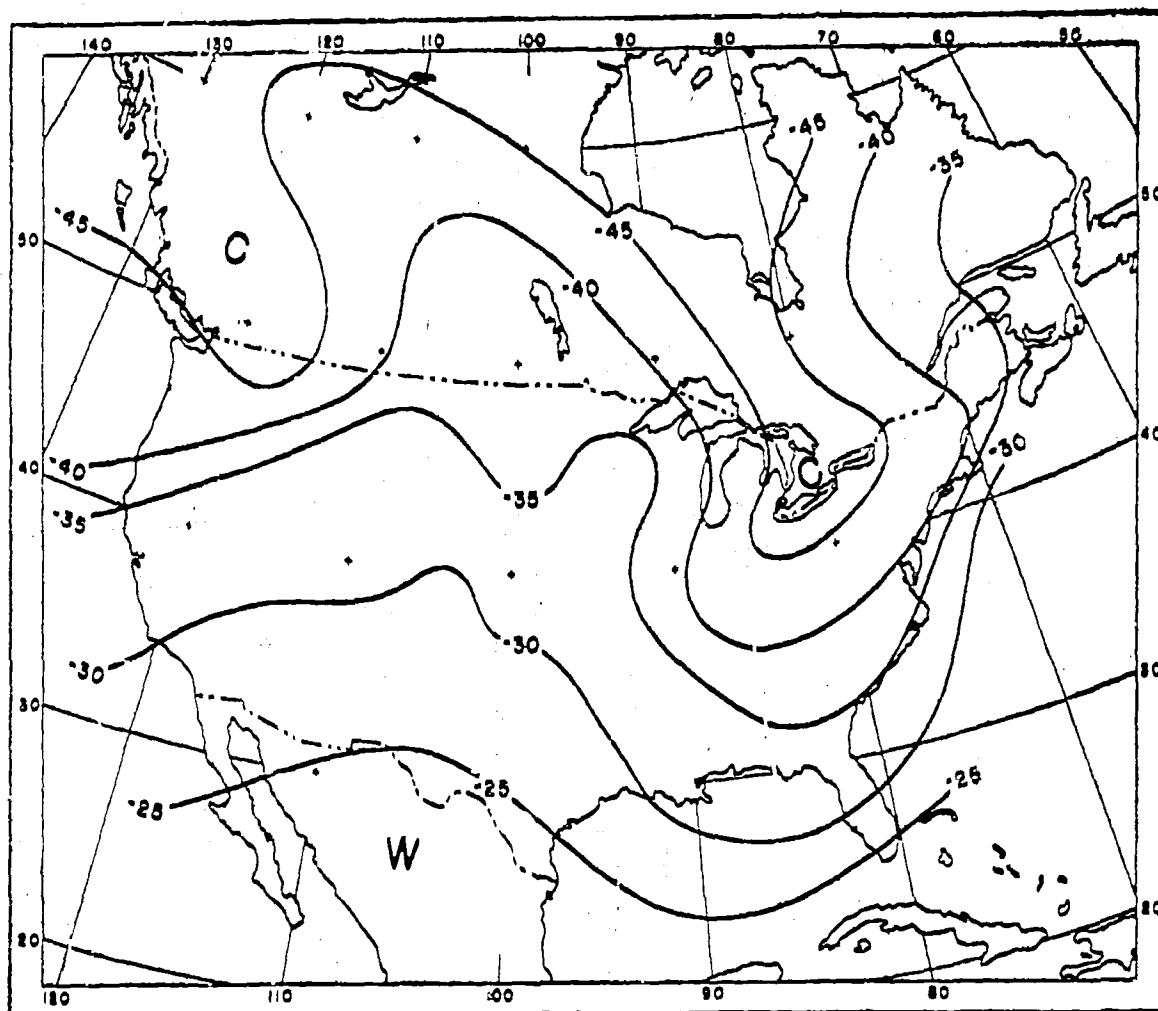


FIGURE 10c. 400-mb Isotherms for 0300 GCT, 18 January 1951.

The tropopause intersections on the 200-mb and 800-mb charts are shown in figures 10d and 10e. The 800-mb chart is mostly in the troposphere, the tropopause intersection lying far to the north. South of the intersection the temperature field resembles that at 400 mb except that the gradients of temperature and the amplitude of the isotherms are smaller. At 200 mb the tropopause intersection is well marked, not so much by temperature minima, as by a pronounced change in the temperature gradient in the 200-mb surface, from very weak gradients on the tropospheric side of the intersection to relatively strong ones on the stratospheric

side. On some charts these strong gradients on the stratospheric side of the intersection become phenomenal, with correspondingly large vertical wind shears, sometimes reaching values in excess of 10 knots per thousand feet over considerable depths. In the troposphere at 200 mb there is very little horizontal temperature gradient, in general, as well as on this chart. Here the gradient is especially weak. The unusual nature of this situation is possibly due to the fact that the tropopause is nearly flat and very close to 200 mb over a considerable distance, as can be seen from the tropopause chart, figure 10a.



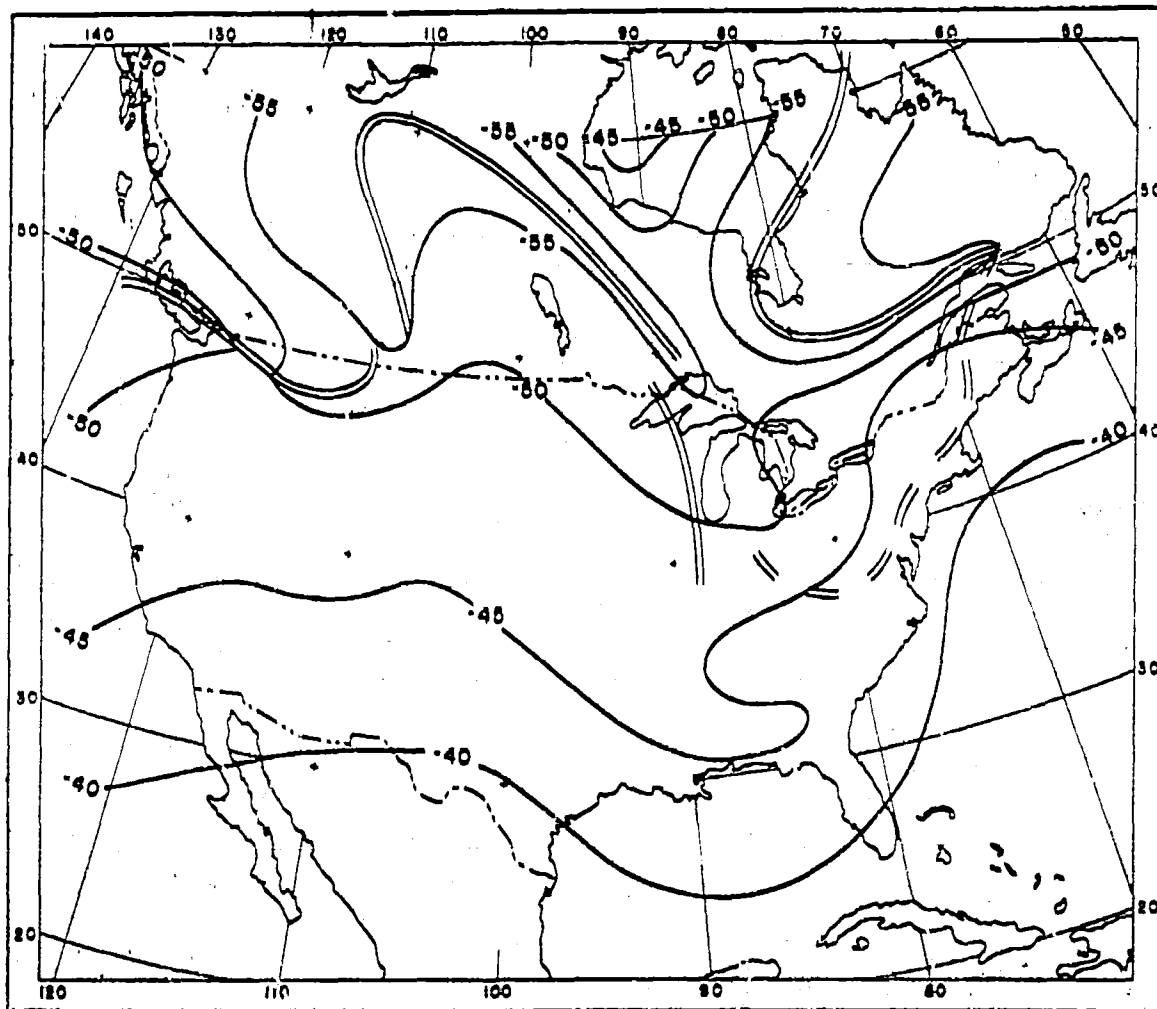


FIGURE 10d. 300-mb Isotherms for 0300 GCT, 18 January 1951. Double lines are tropopause intersections. Dashed double line indicates a break-line at 300-mb, i.e., a line dividing stratosphere from troposphere at 300-mb but where no tropopause intersection occurs.

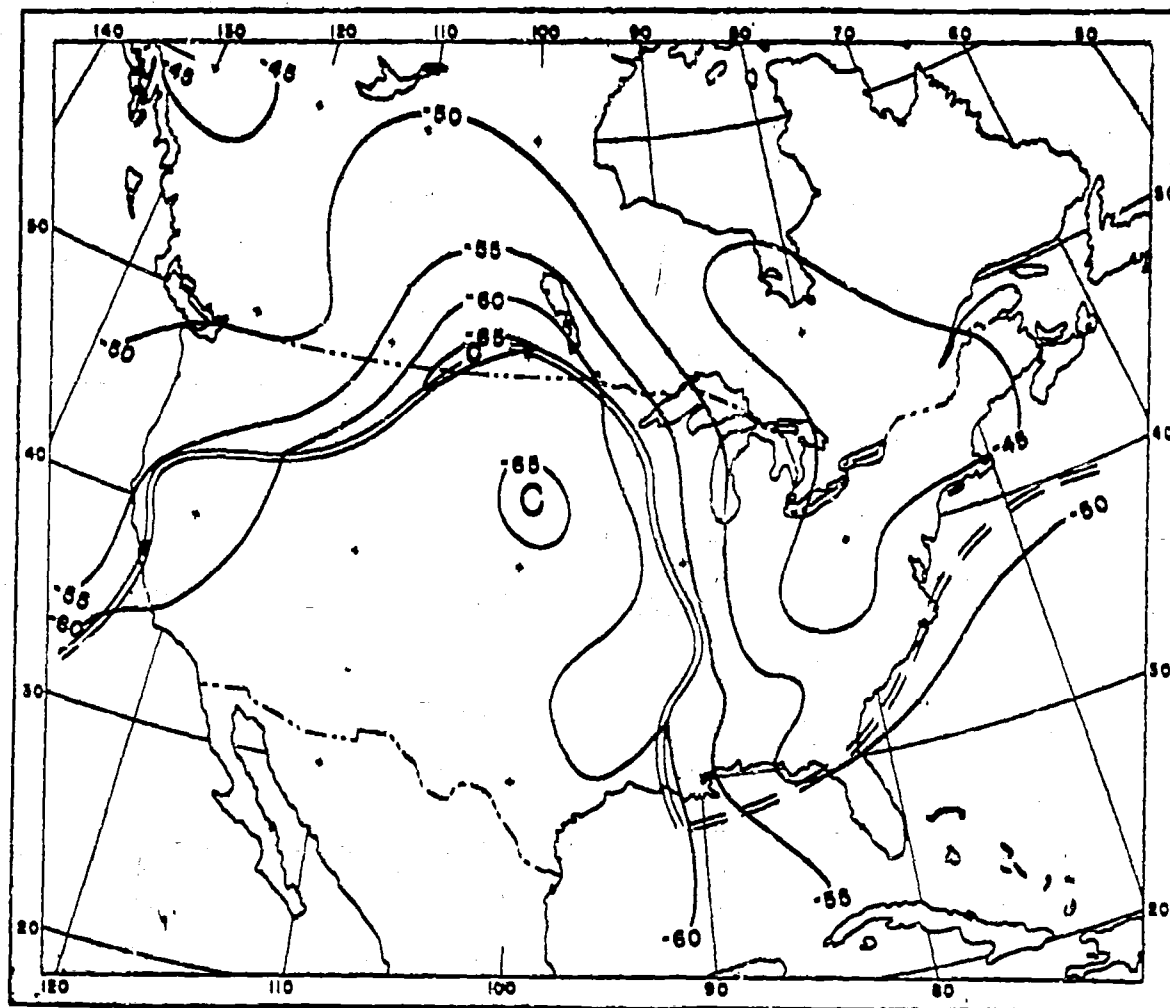


FIGURE 10e. 200-mb Isotherms for 0300 GCT, 16 January 1951.

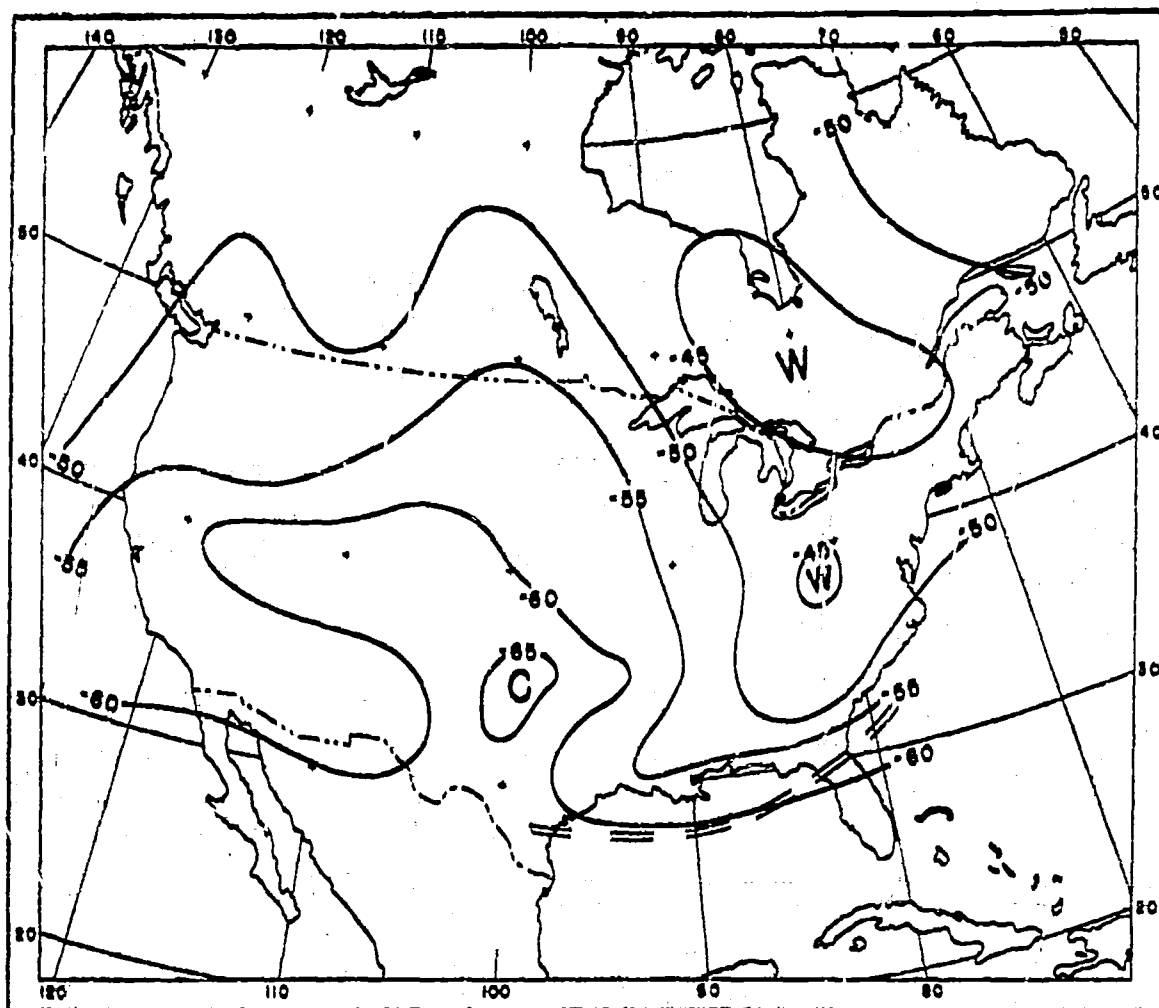


FIGURE 10f. 150-mb Isotherms for 0300 GCT, 16 January 1981.

## Section VII. CONSTRUCTING THE PROGNOSTIC TROPOPAUSE CHART

To date only a limited amount of information is available on methods of forecasting the tropopause height. The correlation between pressure in the high troposphere and the height of the tropopause offers a forecasting possibility. However, Portig (sec. VIII, ref. 11) points out that the existence of this correlation does not lead to a similarly high correlation between the 24-hour changes of these quantities. It can be seen from inspection of the daily charts that the relation between height changes at a surface such as 800 mb and height changes of the tropopause is not dependable, being sometimes definite and sometimes very doubtful.

In preparing 24-hour forecasts of the tropopause-height distribution a few preliminary indications of some value have been found. The first step is the plotting and analysis of the 24-hour changes of the tropopause for the last several days. In doing this sufficient accuracy is obtained by plotting the change values at each station and then drawing continuous lines connecting equal values. This is not a strictly correct procedure in view of the fact that break-lines are drawn on the tropopause charts. A more exact method of obtaining the changes would be the graphical subtraction of a tropopause chart from the previous one with all discontinuities being entered correctly, but the extra effort involved does not seem noticeably to improve the results.

The next step in the forecast procedure is the preparation of a 24-hour 200-mb or 300-mb prognostic chart. For best results this should be done very carefully, using all available aids. The present and forecast velocity fields should be represented by isotach analysis (see AWS Manual 105-23).

The height changes of the tropopause can then be forecast to move in paths extrapolated along the 200-mb flow, and traveling a distance equivalent to the previous 24-hour travel of the change centers, their speed being increased or decreased by an amount proportional to the increase or decrease of the 200-mb winds. The intensity (and size)

of the change patterns can be modified according to the following rules:

In a particular locality, the discontinuity of tropopause height at a break-line will increase if the speed of the associated wind maximum at 200-mb increases. If there is a jet stream forming or increasing and no associated tropopause break, a break-line can be expected to form in the vicinity of the wind-maximum. If the speed of the jet stream is forecast to decrease, the tropopause discontinuity at the associated break-line will also decrease. Extensive midlatitude break-lines not closely associated with prominent 200-mb wind-maxima will disappear.

If there is a distinct northward shift of the jet stream (or more generally a shift to the left as one looks downstream) in a particular area, tropopause rises moving into that area will increase in extent and intensity. Tropopause falls moving into the area will decrease or disappear.

If there is a distinct southward shift of the jet stream (or shift to the right as one looks downstream) in a particular area, tropopause rises moving into the area will decrease or disappear. Tropopause falls moving into the area will increase in size and intensity.

On certain occasions contradictory results seem to arise from application of the various indications given above. Thus the rules may lead to surprising forecast patterns which are often actually observed, such as tropopause change centers of opposite sign moving along on opposite sides of a tropopause break-line.

The above forecasting indications were derived mainly from analysis of the numerous vertical cross sections published in recent years relating the thermal structure of the atmosphere to the wind field. In practice they have given results which have been useful in forecasting, and if applied properly will enable the preparation of a forecast considerably better than persistence. They should, however, be regarded as preliminary indications until better ones are developed.

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Note. An extensive bibliography on the tropopause will appear shortly in the *Meteorological Abstracts and Bibliography*, published by the American Meteorological Society.

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